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**Olive (*Olea europaea*) tree growth and development and the effect
of intercropping with wheat (*Triticum aestivum*) or wheat
undersown with white clover (*Trifolium repens*)**

A thesis
submitted in partial fulfilment
of the requirements for the Degree of
Master of Applied Science

at
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by
Jingrui Wang

Lincoln University

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Abstract of a thesis submitted in partial fulfilment of the
requirements for the Degree of Master of Applied Science.

Olive (*Olea europaea*) Tree Growth and Development and the Effect of
Intercropping with Wheat (*Triticum aestivum*) or Wheat Undersown with White
Clover (*Trifolium repens*)

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The study reported in this thesis was carried out during 2018/2019 at Lincoln University, New Zealand, to investigate olive growth and development and wheat yield profomence in an olive wheat intercropping system.

This experiment was laid out in a split design with three replicates. The main treatments were olive (*Olea europaea*) intercropped with wheat (*Triticum aestivum*), olive intercropped with wheat undersown with white clover (*Trifolium repens*) and fallow used as a control. Sub plots were three olive cultivars Frantoio, Leccino and Barnea.

The main intercropping treatments had no significant effect on olive shoot elongation, leaf apperance, fresh and dry leaf weights and leaf nutrient contents. However, there were significant differences in leaf weight and nutrient content among cultivars. Leccino had the highest fresh and dry leaf weights.

In terms of nutrient content, Barnea leaves contained the lowest nitrogen, phosphorus, potassium. Frantoio had the higest content of potassium and Leccino had the highest phosophorus content. It suggests that olive leaf could be used as animal fodder due to their high mineral content.

This research suggests that undersown clover had no effect on wheat final yield and grain quality. When wheat is intercropped with olive, the wheat yield is likely to reduce by 25% because the tree canopy

reduced the available radiation to wheat. However, it is likely that wheat grain quality will be improved by tree shading.

Wheat canopy and phenology modelling suggests that in the Canterbury region at least, in an olive – wheat intercropping system, earlier wheat sowing is likely to result in a higher wheat yield. Late sowing is likely to increase the grain quality but also increase the nutrient competition between the wheat and olive trees.

Keywords: agroforestry, intercropping, growth and development, shoot elongation, leaf appearance, leaf nutrient content, olive tree, Frantoio, Leccino, Barnea, wheat, clover, canopy ground cover, tree fodder, yield, grain quality, phenology, incident radiation, nutrients competition.

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Chapter 1. Introduction

Global population rise has contributed to a number of land use pressures. Meanwhile, the increasing demand for food, accompanied by climate uncertainties, continues to threaten food security around the world (USDA National Agroforestry Center, 2012). Agroforestry systems have been identified as an effective way to mitigate land pressure and climate change issues for food production.

Nowadays, agroforestry has been widely adopted in several countries. In Greece, farmers have an historical practice of combining olive trees with cultivated land (AGFORWARD, 2014). More recently, there has been an increasing interest in intercropping annual crops with olive trees in several parts of Greece (AGFORWARD, 2014).

Olives (*Olea europaea* L.) are one of the most extensively cultivated fruit crops in the world (Aguilera & Ruiz Valenzuela, 2013). In 2011, the area planted with olive trees was about 9.6 million hectares globally. This is more than twice the land dedicated to apples, bananas or mangoes (Food and Agriculture Organization, 2012). This species was brought to New Zealand by early European settlers in the 1830s and there are currently around 400,000 olive trees in this country (Olive New Zealand, 2019).

When commercially grown as a monoculture, growers in New Zealand often face the economic risks brought about by the “off” year, when the fruit production is low or even nil. Nevertheless, to this day, olive intercropping systems have not yet been explored as a viable option in this country. Considering this, the intercropping of annuals using agroforestry principles and designs could represent an opportunity for improving land productivity in New Zealand olive groves.

One way to increase land agronomic productivity is to use the available biotic (e.g. nitrogen fixing bacteria in symbiosis with the roots of legume plant species) and abiotic (e.g. incident radiation, air and soil temperature, water) resources to its potential (Mao & Zeng, 2019). For that purpose, legume species are commonly used for its ability to fix nitrogen from the atmosphere

(Ito et al., 1997). Moreover, the available light to each individual species, for instance, is a key abiotic resource for production when water and nutrients are non-limiting factors in these systems (Mao & Zeng, 2019). It follows that the quantification of this yield parameter is crucial for planning, establishing and managing of agroforestry systems (Mao & Zeng, 2019). However, this is only possible by understanding the phenology, or ontogeny, of the different species used in the system. This allows to determine the different species demand for crucial abiotic resources in time and space. Moreover, soil and air temperature can be used to quantify critical phenological stages for the crops and the trees. From this, opportunities and constraints can arise for the production of each species in consortiated stands.

Therefore, three hypotheses are presented here: (i) if intercropping influences olive yield production, then it must impact its vegetative growth and/or development; (ii) if the key parameters required for spring wheat growth, development and yield are available in the rows between the olive trees, then it is possible to assume that there is an opportunity to be gained from intercropping wheat in the olive grove; (iii) if legume species are able to improve soil nitrogen, then the olive and wheat yields might benefit from legume intercropping.

The aim of this research was to determinate the olive (*Olea europaea*) tree growth and development and the effect of Intercropping with wheat (*Triticum aestivum*) or wheat undersown with white clover (*Trifolium repens*).

The objectives were:

One: To investigate how different intercropping systems influence the olive vegetative growth and development and to quantify some key olive phenological stages throughout the spring - summer growth season (Section 3.7). Different olive cultivars were used to increase the range of treatments applied and to further determine their potential use as animal fodder. This section details measurements of olive shoot elongation, rate of leaf appearance, leaf chlorophyll concentration, leaf stomatal conductance, leaf dry matter and leaf nutrient content for the different treatments.

Two: To quantify the main phenological stages of milling wheat growth and development and subsequent yield, when intercropped with olive trees and undersown with white clover (*Trifolium*

repens) (Section 3.6). This section details measurements of wheat emergence, canopy ground cover for light interception, flag leaf and flower initiation and final grain yield and quality.

Three: To quantify the influence of different milling wheat sowing dates on crop performance when intercropped with olive trees (Section 3.8). In this section, a sensitivity analysis was carried out based on a milling wheat phenological model created.

1.1 Thesis Structure

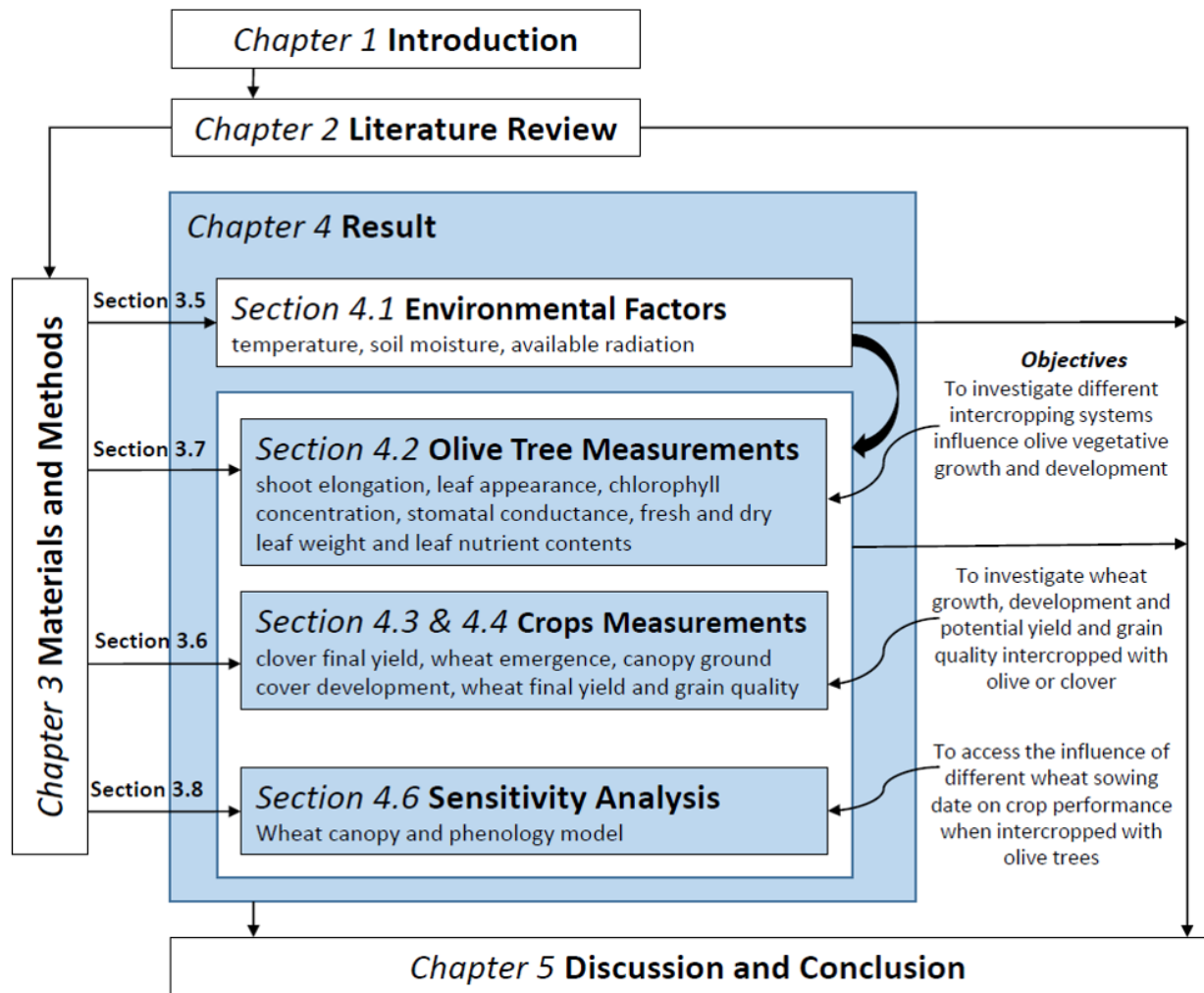


Figure 1.1 Outline of thesis structure and main topics dealt with in each results chapter

Chapter 2. Literature Review

2.1 Agroforestry Background

Agroforestry has been described as a production system in which trees, shrubs and crops are intercropped to provide environmental, economic and social benefits. Agroforestry is often referred as a new name for a set of old practices. Until the 1960s, the word agroforestry had not yet been documented in scientific writings (USDA National Agroforestry Center, 2012). In 1977, a report entitled “Trees, Food and Humans” (part of the Tropical Forestry Research Priorities Project) was published by the Canadian International Development Research Center, which described the key role of trees in sustaining agricultural production in the tropics. This led to the establishment of the International Centre for Research in Agroforestry (ICRAF). In 1982, in order to provide global research opportunities in emerging fields, ICRAF launched the Journal of Agroforestry Research. In 2002, ICRAF changed its name to the World Agroforestry Center to reflect its global mission (Gold, 2017).

There have been many attempts to define agroforestry and these definitions have been constantly revised and improved (Leakey, 1996; Somarriba, 1992). According to ICRAF, agroforestry is defined as “a land-use management system in which woody perennials are deliberately integrated with crops and/or animals on the same land-management unit (Leakey, 1996). In agroforestry, woody and non-woody components always have ecological and economic interactions (Sanchez, 1995). Agroforestry is a unique approach to land management that provides opportunities for landowners to achieve productivity and profitability goals through environmental management, thereby creating a healthy, sustainable agricultural system that can be passed on to future generations (USDA National Agroforestry Center, 2012).

2.1.1 Agroforestry Systems and Plant Phenology

In agroforestry systems, trees and crops can have overlaps in resources demand, resulting in strong competition and reduction in production (Mao & Zeng, 2009). Successful agroforestry systems must consider the differences in species' phenological characteristics, including different physiological needs is complementary to the resource used (Ong et al., 1996). Competition

between species is divided into above-ground and underground competition. Above-ground competition is light competition between trees and crops. Underground competition is the competition for water and nutrients in the soil. Therefore, the competition between light, water or nutrients between components of agroforestry systems is the main determinant of system success (Sanchez, 1995).

Light competition occurs mainly through the process of shading produced by the canopy of the tree. This leads to changes in the quantity and quality of the transmitted light with a reduction of the photosynthetically active radiation (PAR) that limits the crop's ability to yield (Sudmeyer & Speijers, 2007). In agroforestry systems, it is possible to reduce the competition of light by pruning, increasing the spacing of trees, changing the direction of tree planting, and selecting species with strong shade tolerance to improve crop yield (Mao & Zeng, 2009). The wheat C₃ photosynthetic pathway is better adapted to cool and humid environments that tolerate the agroforestry system's shaded conditions better compared with C₄ species (Zamora et al., 2008). Water or nutrient competition can be reduced by irrigation and fertilization (Lehmann et al., 1998). Also, a reasonable species match by avoiding overlapping in nutrient demand phases can reduce nutrients competition (Mao & Zeng, 2009).

2.1.2 Agroforestry Practices

Shifting cultivation refers to the natural regeneration of land following a phase of vegetation clearing and crop cultivation (Nair et al., 1979). The lengths of regeneration phase (also called the fallow or bush fallow phase) vary widely. The regeneration phase (10-20 years) is several times longer than the planting stage (2-3 years) and the length of the fallow is the key to practical success and sustainability (Nair et al., 1979).

The term taungya was originally used to describe transfer farming in Myanmar, but due to its widespread use in the tropics, it has developed into a description of planting trees (Blanford, 1958; Nair et al., 1979). The taungya system is often referred as a stepping-stone in the transition from shifting cultivation to agroforestry. While shifting cultivation is a continuous system for

growing woody species and crops, taungya involved combining the two components simultaneously in the early stages of forest plantation establishment (Nair et al., 1979).

2.1.2.1 Alley Cropping

During the period 1980-1990, alley cropping systems emerged for the development of agriculture in humid and sub-humid tropics (Nair et al., 1987). Alley cropping consists of growing food crops between shrubs and trees (hedgerows), especially with leguminous species (Nair et al., 1979). Therefore, it is a form of hedge intercropping that combines the regenerative properties of bush fallow systems (see section 2.1.2, first paragraph) with the production of food crops.

Alley cropping was first developed by Kang and Wilson (1987) at the International Institute of Tropical Agriculture in Nigeria. Its core idea was to create soil conditions similar to the stage in the fallow phase of shifting cultivation. This was achieved by using fast-growing, nitrogen-fixing, trees and shrubs with cropping, to improve soil physical and chemical attributes while suppressing weeds and controlling soil erosion (Nair et al., 1979). In the 1990s, alley cropping was common in areas of the tropics and temperate zones as described in the review of Lawson and Kang (1990).

As mentioned earlier, different types of agroforestry systems have been used in various parts of the world. In order to adapt to different natural ecological, economic and social environments (Nair et al., 1979), the design of the system has ranged widely in their levels of complexity and adaptability, as described below.

2.1.3 Current Agroforestry Systems

2.1.3.1 *Paulownia elongata* Based Agroforestry Systems

A very successful tree-based intercropping system in China, the wheat - *Paulownia elongate* System (WPS) was reported by Wang and Shogren (1992). This system first appeared in the western part of Henan province in the late 1970s and then spread rapidly across the country. It is mainly used by the farmers or landowners in the middle and lower reaches of the Yellow River, where soil is of low fertility and prone to erosion. WPS has been claimed to increase farmers'

incomes by increasing crop production, improving crop quality and producing more saleable products. According to Wang and Shogren (1992) WPS is also a strategic alternative in areas with limited arable land where there is large demand for food and timber. Newman et al. (1997) carried out an experiment intercropping corn and ginger with *Paulownia elongata*. Compared with the corn grown as monoculture, the intercropping system resulted in 32% reduction in corn, but the yield of ginger increased by 34%.

2.1.3.2 Coffee – Banana Agroforestry Systems

According to Van Asten et al. (2011), coffee - banana systems (CBS) can provide better economic benefits to farmers than coffee monoculture and the productivity and returns of these agricultural systems are higher. In the Arabica coffee growing areas, the average annual return (on a hectare basis) for different planting methods is: intercropping 3,421 USD, banana monoculture 2,092 USD and coffee monoculture 1,552 USD (Van Asten et al., 2011). In the Robusta coffee growing areas, the annual return is: intercropping 1,576 USD, banana monoculture 915 USD and coffee monoculture system 1,293 USD (Van Asten et al., 2011). Zake et al. (2015) found that CBS has the ability to improve soil fertility and carbon sequestration. In their study, the total organic carbon content of the top and subsoil layers of the CBS was higher than that of bananas monoculture (36% and 33%, respectively). The total N of both soil layers was also higher in CBS compared with monoculture (50% and 33%, respectively) (Zake et al., 2015).

2.1.3.3 Cacao (*Theobroma cacao*) Based Agroforestry Systems

Agroforestry systems are also often used in cacao production. Somarriba and Beer (2011) tested two systems: timber or legume intercropping with cacao as shade tree. The results of their experiments showed that the yield of this system was higher compared with the monocropping (Somarriba & Beer, 2011). Koko et al. (2013) reported that cacao - fruit tree intercropping can increase the production of cacao. In their study, the regional average dry cacao yield was 650 kg ha⁻¹ year⁻¹, while the average dry cocoa yield of cacao-orange intercropping and cacao-avocado intercropping were 1,340 kg ha⁻¹ and 1,250 kg ha⁻¹, respectively.

2.1.3.4 Olive (*Olea europaea*) Based Agroforestry Systems

Olea europaea are widespread in southern Europe and they form a continuous landscape element. Agroforestry systems using annual crops and olive trees has been reported for centuries in that part of the world. In Roman times wheat was grown between the olive rows on alternate years. It was believed that this would increase the yield of olives in the following year (Eichhorn et al., 2006). In order to improve overall productivity, the olive grove was divided into two parts during the rotation (Lelle & Gold, 1994). In Greece, at present, where the total area of olives is 650,000 hectares, cereals, vegetables, and fodder crops are commonly intercropped with olive (Schroth & Sinclair, 2002). Similar intercropping systems are found in the central Italian regions of Umbria and Lazio, where olives are commonly intercropped with cereals or fodder legumes; these agroforestry systems cover an area of about 20,000 hectares (Eichhorn et al., 2006). Daoui and Fatemi (2014) surveyed farmers in Morocco and described that legume crops do not affect the yield of olive trees, but cereals often reduce it.

2.1.3 Benefits of Agroforestry

It is frequently mentioned in the literature that agroforestry benefits crop yield, soil and water. Moreover, recently, it has attracted the attention of farmers, researchers and policy makers (Fanish & Priya, 2013). The following sections focus on four major beneficial aspects of agroforestry: carbon sequestration, biodiversity conservation, soil enrichment and effective use of nutrients.

2.1.3.1 Carbon Sequestration

Carbon sequestration refers to the removal and storage of carbon from the atmosphere in carbon sinks such as oceans, vegetation or soil, by physical or biological processes (Kirby & Potvin, 2007). In 2018, the New Zealand government proposed a project called 'The One Billion Trees Programme'. The goal of this project is to increase the current rate of tree planting over in the next decade (Forest New Zealand, 2018). Compared to mono-cropping or pastures, introducing trees or shrubs into the system can increase carbon sequestration (Sharrow & Ismail, 2004). In addition to the carbon stored in above-ground biomass, agroforestry systems also have the ability to store carbon underground. In recent years, Takimoto et al. (2008) and Murthy et al.

(2013) have reported the potential for carbon sequestration from agroforestry Systems. According to Dixon (1995), there is the potential to establish agroforestry systems on approximately 585 - 1,215 million hectares of land in Africa, Asia and the Americas, from which 1.1 - 2.2 peta-grams (Pg) of carbon (vegetation and soil) could be sequestered within 50 years.

2.1.3.2 Biodiversity Conservation

Agroforestry system provides life support through their components such as trees, crops, grass, and livestock. In New Zealand the one 'The One Billion Trees Programme' also aims to provide habitat for native species with the introduction of trees that can benefit biodiversity conservation (Forest New Zealand, 2018). McNeely and Schroth (2006) reported that the level of biodiversity of agroforestry systems is lower than that of original forests, but higher than monoculture.

2.1.3.3 Soil Enrichment

Agroforestry has the potential to enhance and sustain long-term soil productivity and sustainability. The incorporation of trees and crops capable of nitrogen fixation has been widely used in tropical agroforestry systems (Jose, 2009). Sharrow (1999) has reported that the annual nitrogen fixation rate of temperate pastures exceeds 350 kg N/ha. The physical, chemical and biological properties of the soil can be enhanced by adding above ground and underground organic matter and releasing and recycling nutrients in the agroforestry systems. The impact of agroforestry on tropical soil has been well documented (Buck et al., 1998; Schroth & Sinclair, 2002). According to Udawatta et al. (2008), compared with row crops, agroforestry systems have been shown to improve soil aggregate stability, soil carbon, soil nitrogen, and soil enzyme activity.

2.1.3.4 Efficient Use of Nutrients

In agroforestry systems, trees can uptake mineral nutrients that penetrate below the rooting area of the crop and this process, called deep nutrient capture, can reduce losses from drainage (Livesley et al., 2004). Black walnut trees, for example, can capture nitrogen in deep soil leachates (Von Kiparski et al., 2007). Some nitrogen-fixing trees capture nitrogen from the atmosphere and convert it into organic compounds. Tropical plantations capture between 43 to 581 kg of nitrogen/ha annually (Danson et al., 1992). Moreover, reportedly *Acacia mangium* in Brazil can fix 66 kg of nitrogen/ha annually (Bouillet et al., 2008) and 121 kg in Indonesia

(Wibisono et al., 2015). Specific trees also enable crops to absorb phosphorus from the soil. The *Lupinus albus* L., for example, can mobilize phosphorus from deep soil by exuding organic acids in the roots or by mycorrhizal hyphae, increasing phosphorus availability to crops (Watt & Evans, 1999). The nutrients remobilized within those plants are later returned to the soil through above and below-ground tree litter. This is evidenced by the study of Murthy et al. (2013). In their experiment, after applying 10 tones of fresh leaves of nitrogen-fixing trees per hectare annually to a lowland rice system, soil fertility and crop yield increased after three years. This result equaled or surpassed the outcomes of applying a conventional nitrogen-phosphorus-potassium fertilizer.

2.2 Tree Fodder

Trees, typically leaves, have been used as livestock feed for many years (Charlton et al., 2003). Examples can be found, in Africa (Le Hou  rou, 1980), Australia (Turnbull, 1986), India (Tejwani, 1988), Indonesia (Ivory & Siregar, 1984), Nepal (Ng, 1989), and Thailand (Topark-Ngarm & Gutteridge, 1986). In Australia, farmers experienced droughts that have lasted for several years. In such areas the animals have benefited from drought-tolerant trees as a food source (Charlton et al., 2003). During a drought, the leaves of trees usually suffer from premature abscission. Trees shed leaves to reduce transpiration. Compared with other pastures during this period, the fallen leaves are fresh and palatable. Kemp et al. (2003) reported that in New Zealand veronese poplar (*Populus deltoides x nigra*) and Tangoio willow (*Salix matsudana x alba*) provided feed for the sheep and their nutrition of value is similar or higher to pastures.

2.2.1 Leaf Nutrients

Tree fodder contains dietary nitrogen, minerals, energy and vitamins (Devendra, 1992). Cheema et al. (2011) analyzed the nutrient content of fodder tree leaves including *Morus alba*, *Acacia nilotica*, *Syzygium cumuni* and *Ziziphus jujuba*. The Chemical composition of these species included organic matter, crude protein, fibers, hemicellulose and metal elements indicating that they could offer additional advantages as an animal fodders for animals (Cheema et al., 2011). During a drought (summer/ autumn), the nutrient contents of intact leaves fodder of poplars and

willows is usually similar to or higher than the quality of pasture during the same period (Kemp et al., 2003).

2.2.2 Olive Leaves

Olive leaves are a by-product of the trees (Talhaoui et al., 2015). However, there are currently no practical applications for a large number of by-products and residues in the olive tree cultivation and processing industry. In addition, about 25 kilograms of twigs and leaves are produced during pruning. In a typical olive tree pruning process, leaves account for 25% of the total by-product (Govaris et al., 2010). However, these are usually burned or, disposed (García et al., 2003). This common commercial practice is both a waste of valuable resource and a hazard to the environment (Xie et al., 2013).

Xie et al. (2013) determined that the nutrient content of olive leaves (cv. *Frantoio*) and reported as follows:

Table 2.1 Nutrient content of olive leaf (Xie et al., 2013)

| Nutrient | Water | Ash | Protein | Crude Fat | Crude Fiber | Carbohydrates | Polyphenol | Flavonoids |
|--------------------|-------|-----|---------|-----------|-------------|---------------|------------|------------|
| Content (%) | 6.59 | 4.9 | 11.5 | 3 | 15.8 | 52.2 | 1.05 | 1.64 |

Analysis of the metal elements in the olive leaves ash found that it mainly contains calcium (Ca), potassium (K), magnesium (Mg) and phosphorus (P). Among these, the highest content is (Ca) (about 30.5% of ash). Trace amounts of copper (Cu) and iron (Fe) were also found. Furthermore, studies have shown that olive leaves do not contain arsenic (As), mercury (Hg) and lead (Pb) (Xie et al., 2013). In addition, olive leaves also contain special antioxidants (phenolic compounds) such as oleuropein, and flavonoid compounds such as luteolin (Govaris et al., 2010). The concentration of oleuropein, the most inimitable compound in olive leaves, reached 60 - 90 mg/g (Ryan et al., 2002). Markin et al. (2003) demonstrated that these phenolic compounds have significant antimicrobial and antioxidant properties.

Moreover, Xie et al. (2013) concluded that olive leaves can add quality to animal feed. Olive leaves used as animal fodder or nutritional supplements are widely documented. García et al.

(2003) carried out an experiment using olive leaves as fodder for goats and sheep and conducted they are important in the semi-arid regions where pastures are scarce. Morales and Ungerfeld (2015) reported that compounds, especially tannins, in olive leaves can improve meat and milk quality in animals. Abbeddou et al. (2011) and Zilio et al. (2015) showed that milk quality of ruminants such as cow, sheep was improved by adding olive leaf to their diet. Govaris et al. (2010) found that the addition of olive leaves to the diet of turkeys has a beneficial effect on the later phase of meat storage. For turkey that had been fed with olive leaves, the lipid oxidation of raw breasts was delayed for up to 12 days and bacterial growth was inhibited during this period.

2.3 Plant Growth and Development

The growth of plants refers to the increase in the size and weight of cells and plant organs due to cell division and enlargement (Taiz et al., 2015). Plants will stop growing when the organ or part of it reaches a certain size and this is an irreversible process. Differentiation refers to the process whereby generalized cells transform into morphologically and physiologically distinct cells. This process is usually induced by specific conditions, including internal and external triggers (Taiz et al., 2015). Development includes all the changes that a plant experiences during its life cycle, from seed germination to senescence. Therefore, the concept of development encompasses the processes of growth and cell differentiation.

Environmental factors and genetic instructions determine the different patterns of plant development (Taiz et al., 2015). The following sections describe three environmental factors that impact plant development.

2.3.1 Light (Incident Radiation)

2.3.1.1 Influence on Germination

Light influences plant development from the germination stage. Studies have shown that seed dormancy and germination are sensitive to light of certain wavelengths (Pons, 2000). Red light can promote seed germination while far-red light has an inhibitory effect (Borthwick et al., 1954). These phenomena are related to the phytochrome pigment in the seed. Borthwick et al. (1954) have reported that phytochromes are involved in the release of dormancy and the germination of lettuce seeds. Light also affects the growth and differentiation of seedlings.

Light is a signal conduction. For example, during seedling emergence, a dark environment will lead to etiolated growth (Taiz et al., 2015). Symptoms are slender and fragile stems, finely curled leaves, stunted roots and no chlorophyll and therefore no photosynthesis (Hopkins, 1999). Red light can effectively eliminate etiolated growth through promoting the development of young leaves, inhibiting stems' excessive elongation (Taiz et al., 2015).

2.3.1.2 Influence on Leaf Photosynthesis and Yield

Light is a major component of photosynthesis. Visible solar radiation (~400 - 700 nm) on the earth's surface is closely related to plant growth and thus has attracted the interest of plant ecophysiologicalists (Jones et al., 2003). Visible light absorbed by pigment molecules (mainly chlorophyll a and b and carotenoids) drive plant photosynthesis. This light specific wavelength is widely recognized as Photosynthetically Active Radiation (PAR) (McCree, 1971). Monteith and Unsworth (2013) reported that about half of the total amount of solar radiation received is PAR. Under higher light radiation, oxygen has a high affinity for the photosynthetic enzyme Rubisco and binds to Rubisco instead of carbon dioxide. This can reduce photosynthesis through a process called photorespiration (Hay & Porter, 2006).

The photosynthetic rate increases as the light radiation increases until radiation reaches a specific value called the light saturation point. Depending on the mechanism of photosynthesis, plants can be divided into C₃ plant and C₄ plant (Hay & Porter, 2006). Generally, C₄ plants have a higher saturation point than C₃ plants. The first carbon compound produced by C₃ plants during photosynthesis is three carbon atoms. C₄ plants can produce a 4 - carbon compound and provide a higher CO₂ concentration to minimize the photorespiration.

Heraut-Bron et al. (2000) demonstrated that when white clover leaves were treated with higher irradiance (300 - 350 $\mu\text{mol}/\text{m}^2\text{s}$), they achieved a 28% higher weight than leaves treated with lower irradiance levels (100 - 150 $\mu\text{mol}/\text{m}^2\text{s}$). These authors also found that clover shoot biomass of plants was lower when they received lower irradiance. Also, micromolecular substances (glucose, sucrose and amino acids) are synthesized into starch, protein and fat and are stored in cotyledons and endosperm (Coelho & Benedito, 2008). This accumulation depends on leaf photosynthesis (Jones et al., 2003) and the total dry matter accumulation of many crops (including wheat) is proportional to the total amount of radiation intercepted (Cai & Wu, 1993).

During the wheat grain filling period, continuous dull rainy weather results in a significant reduction in yield (grain weight) by influencing the PAR (Cai & Wu, 1993).

The first step in optimizing crop yield and quality is to understand their response to environmental and management factors. In the absence of pests and diseases, weather is a major determinant of crop yield (Monteith, 2000). Moreover, when temperature, moisture, and nutrient conditions are optimum, yields respond linearly to the amount of intercepted solar (Allen & Scott, 1980; Monteith, 1977). This concept allows crop physiologists to describe yield based on four components (Hay & Porter, 2006), as shown in the following equation:

*Equation 1: $Y = R_0 * R/R_0 * RUE * HI$*

where Y is the crop yield, R_0 is the daily incident radiation, R/R_0 is the radiation intercepted by the canopy, RUE (radiation use efficiency) is the overall photosynthetic efficiency of the crop (for example the efficiency of conversion of radiant to chemical potential energy), HI (harvest index) is the fraction of the dry matter produced which is allocated to the harvested parts.

2.3.2 Temperature

The life of a plant is affected by temperature changes as enzymes are important in physiological and biochemical processes and temperature determines their level of activity (Huang, 2005). Only when the optimum temperature is reached is the enzyme most effective in promoting a reaction (Wintrode & Arnold, 2001).

Plant growth is limited to a broad range of temperatures (Gao, 2012). This limitation is related to the cardinal temperatures, which includes a base, an optimal and a maximum temperature (Gao, 2012). Plant development is most effective in the optimal temperature range (Li, 2013). For example, the base and maximum temperatures of wheat crops are 3 - 5 °C and 30 - 32 °C, respectively and the optimal temperature range is 20 - 22 °C (Huang, 2005). In practice this means that, in agricultural production, the most basic agronomic decisions (e.g. time of sowing), should take into account the plant temperature thresholds for growth and development (Gao, 2012).

According to Hay and Porter (2006), dry matter accumulation of a plant can be determined by the following equation:

Equation 2 $P_{net} = P_{gross} - R_{photon} - R_{mitochondrial}$

where P_{net} is the net photosynthesis or dry matter production, P_{gross} refers to the rate of gross photosynthesis, R_{photon} refers to the rate of photorespiration and $R_{mitochondrial}$ is the mitochondrial respiration. Therefore, day and night temperatures can influence plant yield through their influence on the rate of respiration.

In the appropriate temperature range, photosynthesis and respiration increase with increasing temperature and decrease with decreasing temperature. For example, during wheat maturation, the rate of photosynthesis is higher during the daytime with higher temperatures, leading to more organic matter accumulation (Zhao, 2014). With lower temperatures at night, less organic matter is consumed by respiration (Zhao, 2014), leading to higher net photosynthesis. Therefore, in wheat, the greater the daily temperature variation (warm days and cold nights), the higher the yield (Lobell & Ortiz-Monasterio, 2007). For example, the dry matter weight of crops produced in Tibet is higher than that of mainland China, because Tibet has a much greater daily temperature variation (Lu & Yu, 1978).

2.3.2.1 Soil Temperature and Plant Emergence

Seeding emergence may be the most important phenological event affecting the success of annual plants. The time of emergence is an important determinant in the process of crop establishment and further competition for resources (Forcella et al., 2000).

The optimum temperature range for emergence ranges among different crops. For potatoes, for instance, the optimum temperature have been recorded to range from 22 °C (Sale, 1979) to 25 °C (Midmore, 1984). Work by Schneider and Gupta (1985), on the relationship between maize emergence and temperature, showed that the time of maize emergence is extremely sensitive to temperature. At a soil temperature of 20 - 30 °C, the emergence occurred in less than eight days, whereas the lower temperatures (5 - 15 °C) not only delayed emergence by up to 42 days but also reduced the number of plants that emerged. The final percentage of maize emerged at different

temperatures were 87% at 5 to 15 °C and 99% at 20 to 30 °C, respectively, and cold and humid conditions caused seed rot and seedling blight (Schneider & Gupta, 1985).

2.3.2.2 Thermal-time

Reaumur (1735) first described the relationship between plant developmental events and temperature to predict plant phenology and there have been several synonymous terms used to describe the sum of temperatures to predict the duration of plant growth (Nuttonson, 1955).

Thermal-time (Tt) is the common term used for quantifying plant development (Ritchie & Nesmith, 1991). When other environmental conditions such as light and water are favorable, plants must accumulate enough heat in order to progress from one developmental stage to the next. Based on the initial concept of Reaumur, Tt can be divided into two parts which are the accumulation of temperature over a period of time and the plants response to this accumulation. The most basic form of Tt is the linear function of temperature accumulation (Bonhomme, 2000). According to Ritchie and Nesmith (1991), thermal-time can be calculated by the following equation:

$$\text{Equation 3: } Tt = \int_a^b (T_o - T_b)$$

where T_o is the daily mean temperature which is usually calculated using the maximum and minimum daily temperatures. The base temperature is T_b , and a and b are the first and last day of the temperature observations in the experiment, respectively. Muchow and Bellamy (1991) reported that when the daily temperature is higher than the base temperature and lower than the maximum temperature, plant development rates and daily mean temperatures (T_{mean}) conform to a linear relationship.

When plant development is linear with the T_{mean} , it is reasonable to use thermal-time to predicate plant growth and development (Ritchie & Nesmith, 1991). Wheat modelling using Tt has been developed by considerable number of researchers (Hussain et al., 2018; Weir et al., 1984; Xiao et al., 2017). In 1984, Weir et al. demonstrated that it is feasible to use Tt to predict and build a wheat canopy model. Although the influence of vernalization and photoperiod on crops may have an impact on the accuracy of the prediction, Saiyed et al. (2009) reported that

using thermal-time to predict crop growth and development is credible. In their study, thermal-time effectively predicted the time from wheat sowing to anthesis ($R^2 = 0.84$) and grain development to maturity ($R^2 = 0.62$). Therefore, it is reasonable to use thermal-time to estimate wheat canopy development.

2.3.3 Nutrients

The nutrients required for normal growth and development of plants include major nutrients and trace elements. Regardless of their content in plants, they play a vital role in growth and development. Therefore, when plants lack any nutrients, growth and development is inhibited, resulting in reduced yield quality (Taiz et al., 2015).

Nitrogen (N) is found in several important plant components such as amino acids, proteins and chlorophyll. It is key for leaf development and chlorophyll production which is essential for photosynthesis. Boussadia et al. (2010) reported that N can stimulate leaf enlargement. Stunted growth, slow growth, and chlorosis are usually caused by nitrogen deficiency (Roy et al., 2006).

In a similar way, phosphorus (P) is involved in most plant growth and development. Phosphorus exists primarily as a structural component of nucleic acids: deoxyribonucleic acid (DNA) and ribonucleic acid (RNA), as well as fatty phospholipids (Saenger, 1973). These are involved in several important metabolic processes in plants. According to the study of Boussadia et al. (2010), P can enhance leaf enlargement and assists with the growth flowers, helping with reproduction. Also, phosphorus can be used to modify the activity of various enzymes by phosphorylation and for cell signaling (Zhou, 2013).

However, unlike other major elements, potassium (K) is not found in plants' components but is a catalyst and condensing agent for complex substances, an accelerator of enzyme action. Potassium is also involved in stomatal opening and closing to regulate plant water (Arquero et al., 2006). Moreover, K can also stimulate leaf enlargement and delay leaf senescence.

The most prominent role of magnesium (Mg) in plant is its involvement in chlorophyll synthesis. It is the only metal element in the chlorophyll molecule and directly participates in photosynthesis through the formation of chlorophyll (Sirijovski et al., 2006).

Iron (Fe) is also an activator of many enzymes that regulate substance metabolism and energy conversion. Iron is required for photosynthesis and is present as an enzyme cofactor. Without iron, chlorophyll cannot form and leaves will lose greenness, directly affecting photosynthesis (Marsh Jr et al., 1963). Iron is also a component of several enzymes involved in respiration of plants.

2.4 Olive and Wheat Production

2.4.1 Olive Trees

Buds of olive trees shoots can become vegetative buds or flower buds and sprouting of the trees begins at the end of winter. Flowering occurs during summer, and fruiting shoots called inflorescences, originate in the axil of a leaf. Each inflorescence usually contains 10 to 30 flowers depending on the cultivar (Chinese Flora, 1997).

Olive trees produce large numbers of flowers during this period which can last less than a week. Before the flowers open, they go through a period of differentiation, resulting in perfect or staminate flowers. Perfect flowers have both stamens and pistils, while staminate flowers have only stamens and lack a pistil (Breton & Bervillé, 2013). A detailed description of the olive development has been given by Breton and Bervillé (2013) as follows. Flowers can be pollinated in two ways by self-pollination or by cross-pollination. After fertilization, new olive growth begins, and this stage is called the curd stage. During the fruit set period, because the olive tree only keeps those fruits that it can support, withered flowers may also be seen in this time. Fruits begin to harden, until they reach their definitive size and initially-intense green color. As they mature, a color change occurs. The color changing stage is known as veraison and is due to chlorophyll degradation and the accumulation of anthocyanins. Some fruits lost their green tones and turn yellow or pink until they reach a strong garnet or black tone. When the fruit achieves the typical

color of the cultivar, it remains turgid. This time is the harvest maturity and suitable for oil extraction (Chinese Flora, 1997).

Olive trees are a highly alternate (or biennial bearing) species, in that fruits develop on inflorescence which develop from the buds of the shoots from the previous year. Moreover, inflorescences can only develop on well lignified shoots. Therefore, stronger and healthier vegetative shoots from the previous year have great potential to produce fruit (Lavee, 2007). Brown (1994) and Fernandez-Escobar et al. (1999) reported that leaf nutrients in the “off” year (or the year with no fruit bearing) are higher and reduce sharply in the “on” year (or the year of fruit bearing). This is because olive trees need to store nutrition in preparation for the next year’s fruiting. Nitrogen, phosphorus and potassium are the three crucial nutrients for olive yields (Fernandez-Escobar et al., 1999). Nitrogen affects olive yield by influencing fruit set, and leaf nitrogen content, which ranges is from 1.35% to 1.8% (Erel et al., 2013). Phosphorus does not only influence fruit set, but more importantly affects flowering number and the formation of perfect flowers (Erel et al., 2013; Erel et al., 2016; Jiménez-Moreno & Fernández-Escobar, 2017). Unlike other elements, the role of potassium is more likely to affect olive quality (Inglese et al., 2002; Rosati et al., 2015). Potassium can increase the ratio of pulp to peel and increases the weight of the fruit, which leads to an increase in the production of olive oil (Mimoun et al., 2004).

2.4.2 Wheat

Wheat, a C_3 crop, is a highly adaptable and can grow in dry, moist, warm or cold areas, providing a great degree of plasticity. The optimum temperature for wheat development is 20 – 25 °C. The base and maximum temperature are reported as 3 °C and 32 °C, respectively (Huang, 2005) and light saturation occurs when radiation reaches 20 MJ/m² d (Acevedo et al., 2002). Wheat produces side shoots called tillers to build canopy (Acevedo et al., 2002) and bud differentiation into tillers and tiller appearance usually ends before stem elongation begins (Baker & Gallagher, 1983). Different cultivars of wheat have different responses to vernalization. Vernalization has a major impact on winter wheat but little or no effect on spring cultivars such as Sensas used in this experiment (Flood & Halloran, 1986). Most wheat cultivars are sensitive to photoperiod but does not require a specific photoperiod to induce flowering.

According to Zadoks et al. (1974), wheat growth and development can be divided into 10 important development phases including germination, seeding emergence, tillering, stem elongation, booting, ear emergence, flowering, milk development, dough development and ripening. Several important growth stages (GS) during these phases have a major influence on wheat yield. These stages include flag leaf emergence (GS 39), flowering (GS 61) and start of grain fill (grain development) (GS 71) (Hay & Porter, 2006; Zadoks et al., 1974). Evans and Rawson (1970) reported that flag leaves and ears have a major impact on yield, as the carbohydrates needed during grain filling depend on the remobilization of their photoassimilates. Birsin (2005) found that flag leaves are more important than ears for net plant photosynthesis. According to this author, the removal of flag leaves caused a 24% reduction in 1000 grain weight. Therefore, the time of full flag leaf emergence (GS 39) is the most important stage for contributing to yield (Evans & Rawson, 1970; Monneveux et al., 2004; Thorne, 1965).

Nitrogen, phosphate and potassium are three important nutrients during wheat growing season to support canopy growth and latter grain filling.(Roberts & Heady, 1982).

Moreover, the quality of wheat for bread making depends on the protein content in grain (Hay & Porter, 2006). Grain quality can be improved by higher temperature during anthesis (Hay & Porter, 2006; Thorsted et al., 2006) and shade during grain filling (Qiao et al., 2019; Zheng et al., 2013). This is because high temperature inhibition of starch accumulation in the grain has a greater effect than inhibition of grain protein accumulation (Hay & Porter, 2006). According to a study by Triboi and Triboi-Blondel (2002), an increase in temperature from 20 °C to 30 °C during anthesis led to a 27% reduction in grain weight and a 25% increase in grain protein content. Moreover, Zheng et al. (2013) reported that shade can reduce the accumulation of starch and reducing sugars without altering the protein content in the grain, which leads to higher grain protein concentration. Similar results were found by Qiao et al. (2019). They reported an increase in wheat grain protein content from a wheat crop shaded by intercropped with jujube trees (*Ziziphus mauritiana*).

2.5. Agroforestry and the Environment

Forest planting cover an estimated 264 million hectares worldwide (Food and Agriculture Organization of the United States, 2010) from 2000 to 2010. To maximize yields of agroforestry systems, it is important to understand the interactions between multiple plant species and the environment. These interactions can lead to changes for above- and below-ground key resources (e.g. incident radiation, temperature, and nutrients) (Mao & Zeng, 2009). Therefore, the first step in designing an agroforestry system is to understand how these components are influenced by multiple plant species' conformation.

This section will review the three key resources such as incident radiation, temperature and nutrients separately and explore the current understanding of how different agroforestry systems can affect plants performance.

2.5.1. Incident Radiation

In an agroforestry system, tree-height can differ significantly between species. Therefore, the access to incident radiation is highly related to the configuration of the system. For example, the height of trees, spatial organization, density of leaves and branches in the upper canopy, and distance between trees and intercrops all can be influential. When water and nutrients are adequately provided, crop production is limited by the amount of radiation intercepted by the crop (Monteith, 1994; Monteith et al., 1991; Zhang et al., 2014).

In an agroforestry system the photosynthetically active radiation (PAR) that reaches the soil increases with distance from the trees. Nicodemo et al. (2016) found that, for several tree species such as *Peltophorum dubium* *Urochloa decumbens* and *Anadenanthera colubrine*, areas greater than ten meters away from the trees, on average, received more than 90% of the available PAR.

Due to selective absorption by leaf pigments, there is a different radiation spectrum under the tree canopy, resulting in a lower red to far-red ratio (Martinez-Gracia et al., 2010). Schmitt and Wulff (1993) reported that the rich far-red radiation increases apical dominance and inhibits growth of lateral buds. Therefore, the authors concluded that this change in spectrum under the tree canopy could contribute to different yields of crops depended on their distances from trees.

Moreover, low light availability contributes to low crop yields (Barro et al., 2009). Barro et al. (2009) found that slash pine trees (*Pinus elliottii*) had a negative influence on yield of intercropped winter oats (*Avena sativa*). Their shade treatment of 24% and 56% of full light reduced winter oat yields by 25% and 58%, respectively, compared with the full sunlight treatment. Similarly, Kirchner et al. (2010) grew black oats (*Avena strigosa*) in Brazil in an agroforestry system with hairy vetch (*Vicia villosa*) trees in a spacing of 15 x 3 m. They found that the intercropped oat intercepted only 66% and 30% of the total available PAR from the months of March and April, respectively. This resulted in a 43% final yield reduction compared with the control crops grown under full sunlight. Wheat (*Triticum aestivum*) intercropped with *Paulownia elongata* trees has also been reported to negatively influence wheat yield in China (Chirko et al., 1996; Yin, 1997). This was explained by the lower PAR available to the wheat crop from the ten days before flowering until grain filling.

However, agroforestry systems can be optimized to increase light access by pruning and thinning of trees (Everson et al., 2004). In timber trees and maize (*Zea mays*) intercropping, pruning of trees in mid-season of maize crop has been demonstrated to reduce light competition and improve maize yield (Bertomeu, 2012). Adjusting the distance between the trees and the crop can also effectively increase crop yield. Gao et al. (2013) found that increasing soybean (*Glycine max*) and apple tree (*Malus domestica*) intercropping distance from 0.5 to 1.5 m, increased soybean yield by 10%. Yang et al. (2019) found that in a wheat and jujube (*Ziziphus*) tree intercropping system, when they increased the wheat and juju tree distance from 90 cm to 130 cm, wheat yield increased 19%.

However, in an agroforestry systems, crop quality should also be taken into account. Morais et al. (2006) found that coffee intercropped with pigeon pea (*Cajanus cajan*) increased coffee quality. In their experiment, the shading from the tree slowed the maturity of the coffee beans, but increased the contents of caffeine, oil and chlorogenic acid. Moreover, the improvement of wheat quality improved by intercropping with trees has also been well documented (Lu et al., 1997; Qiao et al., 2019; Wang et al., 2015). These researches showed that increased crop shade intensity significantly increases wheat grain protein content which results in benefits for dough development and settling time for processing bread.

2.5.2 Nutrients

In agroforestry systems, trees can access nutrients from deep layers in the soil profile that are not accessible to shallow rooted crops. However, they can also become competitors for nutrient uptake depending on the structure of the roots of the trees.

Existing research shows that competition for soil nutrients in trees and crops has a negative impact on crop performance (Yun et al., 2012). In the Loess Plateau of China, two kinds of walnut and crop agroforestry systems: *Juglans regia* and *Arachis hypogaea* (peanut); *Juglans regia* and *Glycine max* (soybean), reduced around 12% soil nutrient content of 0 to 40 cm depth, resulting in a reduction peanut and soybean yields of 18% and 23% respectively (Yun et al., 2012). Similarly, the *Populus deltoides*, due to its shallow root system, has also been reported to compete for nutrients as well as soil moisture in different crop intercropping systems such as with sorghum (*Sorghum bicolor*), wheat (*Triticum aestivum*) and sugarcane (*Sachharum officinarum*) (Nandal & Bisla, 1995; Singh & Sharma, 2007). Gao et al. (2013) reported that the total organic matter, total N, available P and available K in an apple (*Malus domestica*)- soybean (*Glycine max*) intercropping system was reduced by 31%, 63%, 56% and 28% compared with their respective monocultures. Gao et al. (2013) also reported that, in an apple – peanut (*Arachis hypogaea*) system, the total organic matter, total N, available P and available K reductions were 18%, 21%, 36% and 8%. In these experiments, the crop yields of both systems were also reduced (soybean 12 - 22%; peanut 11 - 13%). Sharma et al. (2012) found that wheat biomass reduced significantly within three meters of the tree line and improved with increasing distance. The authors attributed these differences to competition for nutrients.

Plant nutrient competition in an agroforestry system can be alleviated by introducing legumes into the system (Lucas et al., 2010). Legumes have the unique biological nitrogen-fixing capacity, so they can capture nitrogen in the atmosphere rather than relying entirely on soil nitrogen (Ito et al., 1997). Biological nitrogen fixation can provide more nitrogen for the growth and development of legumes under different environmental conditions. The legumes residue in the system can supplement the soil with nitrogen after decomposition (Fujita et al., 1992; Ito et al., 1997). Patil and Pal (1988) reported that planting bread wheat in an area previously used for

cowpea intercropping can save 80 kg of N/ha. Nutrient cycling and greater nutrient availability by the incorporation of legumes can therefore be taken advantage of to reduce competition and increase the yield of agroforestry systems.

Livesley et al. (2002) reported that in a senna (*Senna spectabilis*) and corn (*Grevillea robusta*) intercropping system, nutrient competition between these two species was reduced. This can be explained by the roots of senna often heavily infected by vesicular mycorrhiza, which is likely to improve the soil nitrogen content (Livesley et al., 2002) Bouhafa et al. (2015) found that in an olive - wheat intercropping system, olive yield was 1.7 tons/ha and the N and K contents of the olive leaves were 0.3% and 0.6%, respectively. However, in an intercropping system with chickpea and faba bean, olive yielded 3 t/ha and 2.5 t/ha, respectively, and leaf N contents were 0.5% and 0.5%, respectively, and potassium contents were 0.7% and 0.9% which were all higher than wheat intercropping. A vegetative growth improvement also observed by Razouk et al. (2016). In their experiment, when intercropping olive tree with faba bean, tree shoot length improved by 14% to 30% depending on the distances between plants. However, the physiological mechanism driving these differences was not given by the authors. It seems that the benefits of intercropping legume crops and olive trees have been overlooked to this day.

Crop harvesting contributes to the removal of nitrogen from agroforestry systems. In agroforestry systems, the removal of litter and tree prunings also lead to nitrogen loss. According to Livesley et al. (2002), in a *Grevillea robusta* - maize system, 14 kg/ha of nitrogen was removed by tree litter and prunings. Similarly, over 75 kg/ha of nitrogen was removed from their senna hedgerow - maize system. In order to recycle the nitrogen in these leaves, an effective way is eaten by animals as tree fodder. This is because the nitrogen will return to the soil through the faeces of animals.

Moreover, competition for nutrients in agroforestry systems can be reduced when the period for nutrient demand varies between the intercropped species. For example, *Trifolium repens* is productive in late winter to late spring and mid-autumn to mid-winter (Lucero et al., 2000) whereas the growing season for olive trees is typically from spring to autumn (Bouhafa et al., 2015). Therefore, the growth and development of both species will not be influence by nutrient competition. The production of the system is not likely to be reduced.

2.5.3 Temperature and Wind

Shade provided by trees in agroforestry systems can benefit crops during extremely warm days. Temperatures under tree canopies can be much lower than in an open field, reducing heat stress for plants (Lin et al., 2015). Trees have also been reported to act as windbreaks in wheat fields, reducing sandblasting and lowering temperatures downwind (Bennell et al., 2007b). According to Bennell et al. (2007a) flower abortion of faba beans (*Vicia faba*) is increasingly sensitive to wind speeds in the range of 2 - 16 m/s under 30 °C. In their experiment, compared with 2 m/s wind speed treatment, flower abortions from 12.5 m/s wind speeds treatment were 30% and 38% higher at anthesis and earlier flower developmental stages, respectively (Bennell et al., 2007a).

Autstin et al. (1999) reported that soil temperature during the first 50 days after flower bloom affects fruit size in apple trees. This principle also applies to other species of trees including olive and jujube trees. Crop residues left on the soil surface can affect soil temperature in an agroforestry environment. Surface residue can reflect solar radiation and isolate the soil surface from atmosphere resulting in reducing the rate of soil temperature increase (Van Wijk et al., 1959). In a study by Shen et al. (2018), soil temperature and crop residue coverage showed a significant negative linear relationship and for every percentage increase in residue coverage, the soil temperature dropped from 0.01 to 0.03 °C (Shen et al., 2018).

2.6 Agroforestry Modelling

The agroforestry system is a complex system involving multiple competitions (e.g. light, nutrients) among species. The development of a successful agroforestry system must follow the concept that different physiological needs among species is complementary to the resource used (section 2.1.1) (Mao & Zeng, 2009). Therefore, reasonable decision-making is highly important in agroforestry, including species selection and planting time (Atangana et al., 2014).

A successful agroforestry system generally results from years of experimentation. According to Burgess et al. (2019), due to the long growth period of trees, if only relying on experimental data, the development of agroforestry system will be restricted but using an agroforestry model

can solve this problem. The term 'agroforestry model' is explained by the Oxford English Dictionary as a simplified description of a system or process helping calculations and predictions. Until now, agroforestry modelling has been used in considerable numbers of studies (de Jalón, 2018; De Reffye et al., 1995; Lamanda et al., 2008; Mialet-Serra et al., 2001).

In this experiment, wheat canopy/phenology models of different sowing data were developed, based on the thermal-time (section 2.3.2.2), to undertake a sensitivity analysis to investigate the possible effects of different wheat sowing times on an olive and wheat agroforestry system.

Chapter 3. Materials and Methods

3.1 Site Description

An agroforestry experiment with three olive cultivars, intercropped with wheat or wheat undersown with clover was carried out in Canterbury, New Zealand in 2018/2019.

The experiment was a split plot design with three treatments as main plots (wheat, wheat undersown with clover and a Fallow as control) and three tree cultivars (Frantoio (F), Barnea (B) and Leccino (L)) as sub plots as showed in Figure 3.1. Milling wheat (*Triticum aestivum*) and white clover (*Trifolium repens*) was sown on the west and east sides of each row of trees leaving an unsown gap of approximately 1.5 m from the base of the trees. Each side of wheat planting area was 36m² (3 m X 12 m).

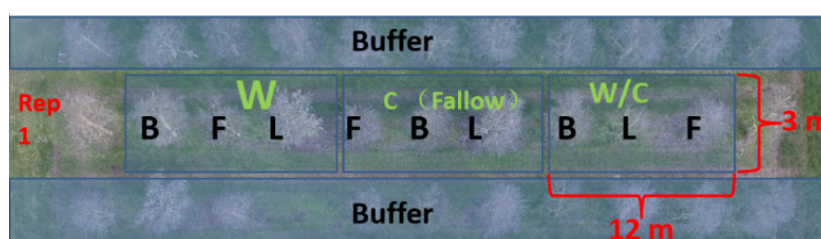


Figure 3.1 Illustration of the field experiment main plots (W-- only wheat; W/C-- wheat undersown with clover; C-- (Fallow)) and the three tree cultivars as sub plots (F-- Frantoio; B-- Barnea; L--Leccino).

Experiments were replicated three times (Figure 3.2). The tree, which had been planted in a north-south arrangement, had an average of height of 3-4 m and a canopy diameter of 2.7 m. In the rows, trees were spaced 4 m apart.



Figure 3.2 Overview of the olive grove. The olive grove located the Lincoln University Horticulture site (43°38'S and 172°27'E) established in 2004. There were eight replicates surround by guard trees. Three replicates were used in this experiment.

3.2 Cultivation

3.2.1 Olive Tree (*Olea europaea*)

Barnea is a fast-growing cultivar which originated in Israel. It is a prolific producer of olives when environmental conditions are appropriate. However, the cultivar is intolerant of cold areas of New Zealand (Waimea Nurseries, 2014). It is used in New Zealand as a pollinating tree.

Leccino and Frantoio are both from Italy and are widely planted in New Zealand. Both have performed well in New Zealand and are favored for their quality oil. Frantoio is self-pollinating and has a strong resistance to disease. It can be used as a pollinating tree. According to a report by Aguilera et al. (2005), Frantoio has good adaptability to different agricultural environments and is highly productive; One drawback is that it is cold-sensitive. By contrast, Leccino is a healthy and vigorous cultivar with a good cold tolerance. However, it is not self-pollinating and has a low resistance to fruit drop (Aguilera et al., 2005; Waimea Nurseries, 2014).

3.2.2 Milling Wheat (*Triticum aestivum*)

The milling wheat cultivar used in this experiment was Sensas, a French bread wheat bred by research company serasem in France and introduced to New Zealand by PGG Wrightson Grain (PGW Grain). Compared with other spring wheat cultivars, Sensas develops quicker. It is commercially sown in August to mid-October (spring) in New Zealand and can be harvested after 3-4 months (PGG Wrightson Grain, n.d). Sensas has moderate tillering ability, high yield and the grain is high in protein. As a spring wheat, it has very good resistance to disease such as stripe rust (*Puccinia striiformis*), powdery mildew (*Sphaerotheca fuliginea*) and rust (*Pucciniales*) (PGG Wrightson Grain, n.d).

3.2.3 White Clover (*Trifolium repens*)

White clover is one of the main species found in New Zealand pastures (Caradus et al., 1996). The advantage of this species is that it provides cheap, abundant nutritive value. As a legume, it fixes nitrogen (Caradus et al., 1996; Massey University, 2016). Therefore, it can provide high

quality feed for animals (Massey University, 2016). According to Caradus et al. (1996), the annual financial contribution of white clover to New Zealand agriculture is \$3,095 million.

3.3 Experimental Site

3.3.1 Location and History

The field experiment was carried out in an olive grove (established in 2004) located at Lincoln University (43°38'S and 172°27'E). Due to the decline in research interest in olives in recent times, the grove had been unmanaged for several years (such as limited pruning and weed control). Also, this study was carried out in typical “off” year in terms of fruit production, so it was not possible to measure this aspect.

3.3.2 Soil

The soil is classified as a Templeton silt loam (Udic Ustochrep, UDA Soil Taxonomy) (McLaren & Cameron, 1996) characterized as a moderately deep soil. The plant available water-holding capacity is approximately 190 mm/m of depth (Jamieson et al., 1995).

3.3.3 Climate

The climate in this area is characterized by a long-term average (LTA) rainfall of 610 mm evenly distributed throughout the year and a mean temperature of 15 °C during the wheat growing season in Canterbury (October - January). Between October and January the LTA evapotranspiration ranges from 96 to 146 mm per month. The meteorological data analyzed in this experiment were measured at the Broadfield Meteorological Station (Plant & Food Research, Lincoln, New Zealand) located about 3 km southeast of the olive grove experimental site.

Table 3.1 Long-term (1999 - 2018) data series for rainfall, Penman total potential evapotranspiration (E_p), daily maximum (T_{max}), minimum (T_{min}) and mean (T_{mean}) temperature and daily solar radiation recorded at Broadfield Meteorological Station, at Lincoln, New Zealand.

| Month | Rainfall (mm) | E_p (mm) | T_{max} (°C/d) | T_{min} (°C/d) | T_{mean} (°C/d) | Solar Radiation (MJ/m ² d) |
|-------|------------------|---------------|---------------------|---------------------|----------------------|--|
| Jan | 45 | 146 | 21.9 | 11.7 | 16.8 | 22.1 |
| Feb | 40 | 112 | 21.7 | 11.8 | 16.7 | 19.2 |

| | | | | | | |
|--------|-----|-----|------|------|------|------|
| Mar | 44 | 88 | 20.1 | 10 | 15.1 | 14.7 |
| Apr | 61 | 45 | 17.2 | 7.5 | 12.4 | 9.4 |
| May | 65 | 27 | 14.6 | 5.1 | 9.8 | 5.9 |
| Jun | 61 | 17 | 12 | 2.3 | 7.1 | 4.6 |
| Jul | 54 | 20 | 11.3 | 1.6 | 6.4 | 5.4 |
| Aug | 59 | 33 | 12.6 | 3.1 | 7.9 | 7.9 |
| Sep | 36 | 61 | 15.1 | 4.9 | 10 | 12.6 |
| Oct | 53 | 96 | 16.7 | 6.4 | 11.5 | 17.7 |
| Nov | 48 | 124 | 18.5 | 8.2 | 13.3 | 22.1 |
| Dec | 50 | 144 | 20.5 | 10.7 | 15.6 | 22.8 |
| Annual | 610 | 916 | 16.9 | 6.9 | 11.9 | 13.7 |

3.4 Three and Crop Managements

3.4.1 Weed Control

On the 30/08/2018, prior to drilling the milling wheat, glyphosate herbicide was applied in the experiment site. During the experiment, weeds were controlled by hand weeding.

3.4.2 Diseases Control

On the 27/08/2018, copper oxychloride at a rate of 300g/100L of water (Yates) was applied to the trees to prevent for fungal and bacterial diseases (e.g. black spot (*Diplocarpon rosae*), fire blight (*Erwinia amylovora*) and leaf curl (*Taphrina deformans*).

3.4.3 Fertilizer Application

Based on the soil analysis, 15 g OrganiBor (Boron content 10%) was applied at the base of each olive tree by hand – prior to the sowing of the milling wheat crop.

Table 3.2 Soil test results for the experimental site in Lincoln, Canterbury, New Zealand from 2018. Olsen Phosphorus measured by Molybdenum Blue Colorimetric. Potassium, Calcium, Magnesium, Boron were 1 M Neutral ammonium acetate extraction followed by ICP-OES. Medium Range stated is from Hills Laboratories.

| Nutrient | pH | Olsen Phosphorus (mg/L) | Potassium (me/100g) | Calcium (me/100g) | Magnesium (me/100g) | Boron (mg/kg) |
|--------------|---------|-------------------------|---------------------|-------------------|---------------------|---------------|
| Soil test | 6.5 | 17 | 0.72 | 6.4 | 2.65 | 0.6 |
| Medium Range | 6.0-6.5 | 15-30 | 0.50-1.00 | 6.0-12.0 | 1.00-3.00 | 1.0-2.0 |

3.4.4 Wheat and Clover Establishment

On the 20/09/2018, wheat was drilled at a rate of 95 kg/ha with a Fiona seed drill at a depth of 25 mm and a row spacing with 75 mm. On the same day, clover crop was sown by hand at a rate equivalent to 3.5 kg/ha, then gently raked over.

3.5 Physical Environmental Measurements

3.5.1 Temperature

From the 20/09/2018 to the 01/07/ 2019, to recorded temperature, a HOBO U12 4-external channel outdoor/industrial logger (ONSET[®], HOBO[®] U12-008 Data Logger) with TMCx-HD water/soil temperature sensors was used to record soil and air temperatures hourly. One sensor was placed one meter above the soil surface to measure air temperature and three were placed 150 mm underground to measure soil temperature in each of the main treatments in the replicate (Rep) 2 (Figure 3.2).

3.5.2 Soil Moisture Content

Soil moisture content at 150 mm depth was recorded weekly in each plot using a HydroSense II Display (Campbell Scientific 658, SN: 33334). One measurement was taken on each side of the tree row (west and east) in each plot.

Rainfall and evapotranspiration values during the experiment were collected from data recorded at Broadfields Meteorological Station at Lincoln, Canterbury, New Zealand. Potential soil water deficit (D) was calculated based on the method of French and Legg (1979), using estimates of Penman's evapotranspiration:

Equation 4: $D = D_o + E_{p_o} - \text{rainfall} - \text{irrigation}$

where D_o is the value on the previous day and E_{p_o} refers to the potential evapotranspiration estimated. No irrigation was used in this experiment.

The potential soil water deficit, calculated for a milling wheat crop with a root depth of 800 mm and daily rainfall are shown in Figure 3.3. During the wheat growing season (September 2018

to January 2019), the soil water deficit was above 70.5 mm, which is the critical soil water deficit for wheat grown in a templeton silt loam soil (Figure 3.3) (Hay & Walker, 1989).

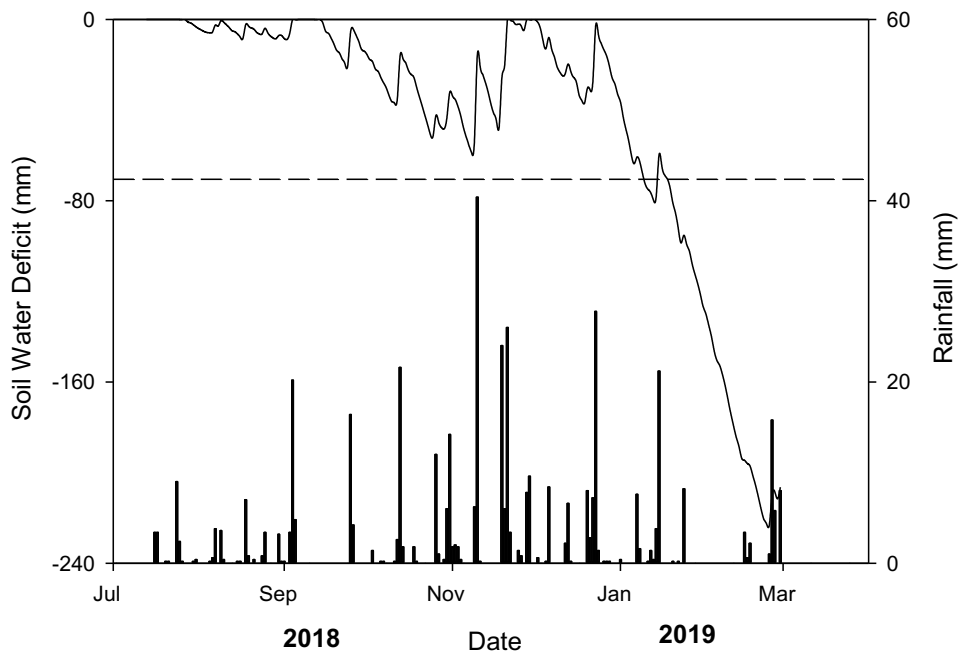


Figure 3.3 Potential water deficit (mm) calculated using daily values of Penman evapotranspiration and rainfall (grey bars) during the experiment (July 2018 to March 2019). Data collected from the Broadfields Meteorological Station (Lincoln, New Zealand). The horizontal dashed line represents the critical soil water deficit for wheat grown in a templeton silt loam soil at 70.5 mm (Hay & Walker, 1989).

3.5.3 Solar Radiation in Canterbury

Monthly total solar radiation in Canterbury from 2018 to 2019 was obtained from the Broadfields Meteorological Station (Lincoln, New Zealand) (Figure 3.4).

Additionally, two line quantum sensors (LI-COR Biosciences, LI-191) were placed in the Fallow plot (Rep 2) (one each side of the olive trees) to record the photosynthetically active radiation (PAR) in the olive grove. A Gaussian, 3 parameter fitted curve ($R^2 = 0.86$) was fitted to these data showed in Figure 3.4 (Red line).

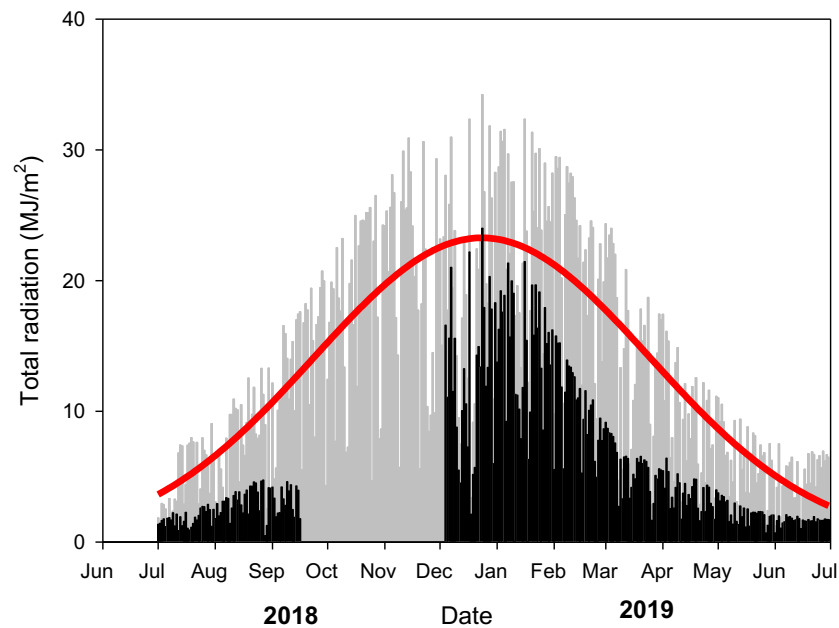


Figure 3.4 Monthly total solar radiation (MJ/m^2) in Canterbury from 2018 to 2019 measured at the Broadfields Meteorological Station (Lincoln, New Zealand) (Grey bar). A Gaussian, 3 parameter fitted curve ($R^2 = 0.86$) was fitted to these data (Red line).

3.6 Annual Crop Measurements

3.6.1 Wheat Emergence

Wheat emergence was determined by counting the number of seedlings visible from the start of emergence. A one-meter standard ruler was used to measure the number of emerged plants within this length, in each plot on the west and east side of each line of trees.

The number of emerged plants was measured from 05/10/2018 and continued until there was no further increase in numbers of emerged plants.

3.6.2 Green Canopy Ground Cover

A GreenSeeker handheld crop sensor (Trimble instruments, California) was used to measure canopy ground cover, based on the normalized difference vegetation index (NDVI) (ranging from 0.00 to 0.99). NDVI is derived from the canopy reflectivity of the red and near-infrared wavebands and was calculated according to following equation:

$$\text{Equation 5: } NDVI = (NIR - VIS) / (NIR + VIS)$$

Gamon et al. (1995) reported that NDVI is a sensitive indicator of canopy structure. As the canopy size increases, chlorophyll and related pigments absorb more visible (VIS) wavelengths (400 - 700 nm), while more near-infrared (NIR) wavelengths (750 - 850 nm) are reflected. Therefore, the measured values can reflect the green canopy ground cover of the crop.

In this experiment, from 5/10/2018 to 24/01/2018, from wheat emergence to harvest, a GreenSeeker handheld crop sensor (Trimble instruments, California) was held one meter above the ground on the mid line from south to north in each intercropping treatment to measure wheat canopy ground cover.

3.6.3 Wheat Growth Stage

Major wheat growth stages such as flag leaf emergence (GS 39), flowering (GS 61) and grain fill (GS 71), were visually assessed and recorded weekly. These growth stages were based on the decimal key devised by Zadoks et al. (1974). For this a total of ten wheat plants were randomly selected on each occasion.

3.6.4 Crop Protection and Harvest

To prevent bird damage, the crops were covered by a 1.5 X 2 m net in each plot after wheat flowering had finished. When the wheat was mature, a 1 m² area from each intercropping treatment (on both west and east sides of the trees) was harvested using hand shears. This took place on 29/01/2019.

Wheat ears from each harvested plot were counted and ten randomly selected ears were used to determine total grain weight and thousand grain weight. From these harvested grains, protein and trace elements content were determined (Hill Laboratories, Hornby, Christchurch, New Zealand).

The white clover was harvested in a similar way as wheat harvest. Fresh weight was recorded at harvest time and plants were later dried in an air circulation oven at 60-70°C for 48 hours. Then, the dry weight was recorded.

3.7 Olive Tree Measurements

3.7.1 Tree Shoot Selection

At the end of November 2018, for each tree, two west-facing and two east-facing branches at a height of approximately 1.5 meters from the ground were selected from the outside of the canopy. A shoot, of approximately 300 mm from the distal end of each chosen branch was then selected and labelled and the marked shoots were monitored throughout the vegetative growing season.

3.7.2 Labelled Shoot Measurements

From 23/11/2018 to 29/05/2019, the following shoot measurements were recorded: shoot length and number of leaves (a leaf was recorded when its lamina was longer than 5 mm). These measurements were carried out at a 10 days interval.

3.7.3 Stomatal Conductance (SC) and Chlorophyll Concentration

From 05/12/2018 to 03/06/2019, stomatal conductance (SC) and chlorophyll concentration measurements were carried out every 10 days on each marked shoot. The youngest leaf which was at least 15mm wide was used with a Leaf Porometer (SC-1, ICT International) to record stomatal conductance. After each measurement of SC, the greenness of the same leaf was measured with a SPAD chlorophyll meter (502Plus, Konica Minolta).

The chlorophyll concentration was determined by the dimethylformamide (DMF) chlorophyll method as described by Inskeep and Bloom (1985). Chlorophyll concentration was calculated by creating a calibration curve using the SPAD readings and the chlorophyll concentration values for each cultivar. A range of leaves with different levels of greenness (from light green to dark green) was used for the calibration curve. Equations were derived using the curve.

3.7.4 Olive Leaf Measurements

On 23/06/2019, olive leaves from both west and east sides of each trees were randomly collected by hands and put in labeled paper bags.

From each bag, 100 leaves (equal to approximately 20 g) were selected to record fresh weight and average SPAD readings. The leaves were then dried in an air circulation oven (60 - 70°C) until they reached constant weight. The leaves were then ground in an Ultra Centrifugal Mill ZM 200 Grinder. The ground samples later analyzed for protein and trace element content.

3.8 Wheat Canopy/Phenology Modelling

The canopy ground cover (CGC) development of wheat sowing on 20/9/2018 was recorded using a Greenseeker during the growing season. These data were fitted by a Piece-wise curves ($R^2 = 0.99$) against thermal-time (Tt) ($T_b=5$ °C). Based on this curve, the Tt from full emergence to maximum canopy ground cover (CGC), Tt for CGC constant, and from maximum CGC to harvest were obtained. Dates of flag leaf emergence (growth stage (GS) 39) and the start of grain fill (GS 71) for sowing on 20/9/2018 were recorded in this experiment. Using actual recorded date, the Tt to these stages were calculated.

Since these Tt for wheat growth and development remain unchanged regardless of sowing date (Saiyed et al., 2009; Xiao et al., 2017), the canopy/phenology models of different simulated wheat sowing dates were created. An example of how this was used for sowing on the 23/8/2018 is described below:

In the model the x-axis intercept (a, Figure 3.5) and the slope of the earliest linear phase, correspond to the time of full wheat emergence and the canopy development rate, respectively. The coordinates (x, y) at which an increase in CGC ceases (b, Figure 3.5) corresponded to the date when maximum wheat CGC reaches and the maximum CGC value, respectively. The constant phase of maximum wheat CGC (c minus b, Figure 3.5) and the time of wheat CGC decrease (d minus c, Figure 3.5) are shown in days (Table 3.3). The constant phase ending point (c, Figure 3.5) represented the start of canopy ground cover decrease. Wheat harvest time was d (Figure 3.5).

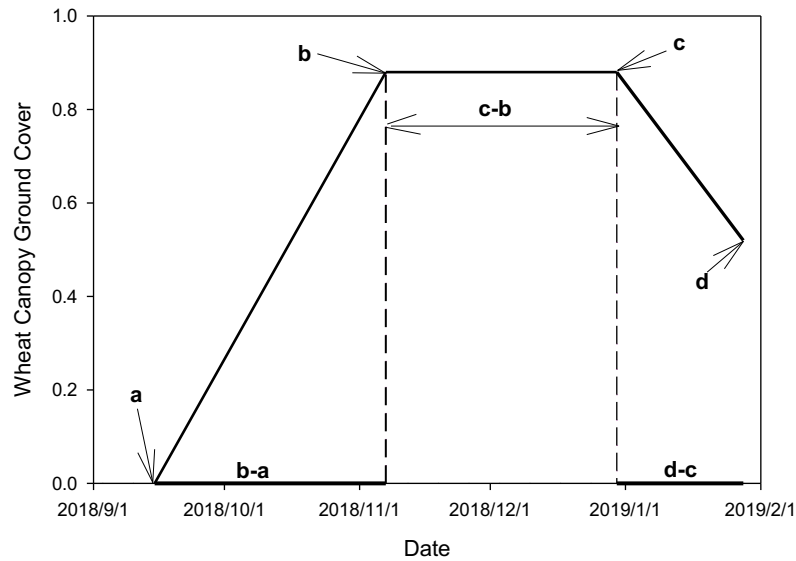


Figure3.5: Example of wheat canopy ground cover (CGC) against date using actual data (Table 3.3). Numbers indicate wheat canopy ground cover changes (0-1 equals 0-100%) and letters indicate CGC increase duration(b-a), maximum CGC duration (c-b) and CGC decrease duration (d-c). The parameters of wheat CGC model from crop emergence to harvest were estimated by the Tt and are shown in Table 3.3. The regressions were performed using a three phase model where a = wheat emergence; b = start of maximum CGC phase; c = end of maximum CGC phase; d = wheat harvest.

Table 3.3 Parameters for creating canopy model of a simulated wheat sowing date (23/08/2018). Numbers of days from full emergence to maximum canopy ground cover (CGC), numbers of day of constant phase last and numbers of days from emergence to harvest were estimated by the thermal-time.

| Sowing date | Number of days to full emergence | Full emergence date | Number of days to Max CGC | Max CGC date | Number of days of constant Phase last | End of constant phase date | Number of days from emergence to Harvest | Harvest date |
|-------------|----------------------------------|---------------------|---------------------------|--------------|---------------------------------------|----------------------------|--|--------------|
| 23/08/2018 | 23 | 15/9/2018 | 53 | 7/11/2018 | 53 | 30/12/2018 | 135 | 28/01/2019 |

Eight simulated sowing dates were used (23/8/2018; 30/8/2018; 6/9/2018; 13/9/2018; 27/9/2018; 4/10/2018; 11/10/2018; 18/10/2018) to created eight wheat canopy/phenology models as described above and were used to undertake a sensitivity analysis for olive wheat intercropping system.

3.9 Calculations

3.9.1 Thermal-time

In this experiment, thermal-time was calculated using the equation: *Equation 3: $Tt = \int_a^b (T_o - T_b)$* (section 2.3.2.2). From the date when wheat was drilled to full crop emergence, thermal-

time (T_t , °Cd) was calculated using the mean daily soil temperature and wheat base temperature for growth (5 °C). From full emergence onwards, mean daily air temperature and wheat base temperature for growth was used to calculate thermal-time.

For olive growth and development, thermal-time was also measured from wheat full emergence and was also calculated using daily mean air temperature and wheat base temperature.

3.9.2 Wheat Total Radiation Interceptance

The wheat canopy ground cover models produced (section 3.8) and the available incident daily radiation for wheat intercropped with olive trees ($R_{o \text{ daily}}$) were used to calculate the total canopy radiation intercepted in MJ/m².

The daily fraction of canopy ground cover (CGC_{daily}) was estimated using the wheat canopy model. Daily values of available incident radiation ($R_{o \text{ daily}}$) for wheat were estimated with a Gaussian, 3 parameter fitted curve.

Crop total radiation intercepted (R_{total}) was calculated by integrating the daily values of radiation interceptance, from crop emergence (em) to harvest (har), according to the following equation:

$$\text{Equation 6 } R_{\text{total}} = \int_{em}^{har} CGC_{\text{daily}} * R_{o \text{ daily}}$$

where $R_{o \text{ daily}}$ is the daily wheat mean available incident radiation.

3.10 Statistical analysis

Data were analyzed using GenStat version 18 (VSN International, UK). Significant differences ($P < 0.05$) among the treatments were determined by analyses of variance (ANOVA) according to the split-plot design (Figure 3.1). A split-line regression was fitted to identify the point of breakage using the same statistical package. Also, piece-wise and gaussian-3 parameter curves were fitted using SIGMAPLOT version 14.0 (SYSTAT Software Inc, UK).

Chapter 4. Result

4.1 Environmental Factors

4.1.1 Temperature

Mean monthly air temperatures ranged from 5 - 20 °C during the course of the experiment from October 2018 to July 2019 (Figure 4.1). January and June had the highest and lowest monthly temperatures, respectively. The largest daily temperature range (11 - 24 °C) occurred in January.

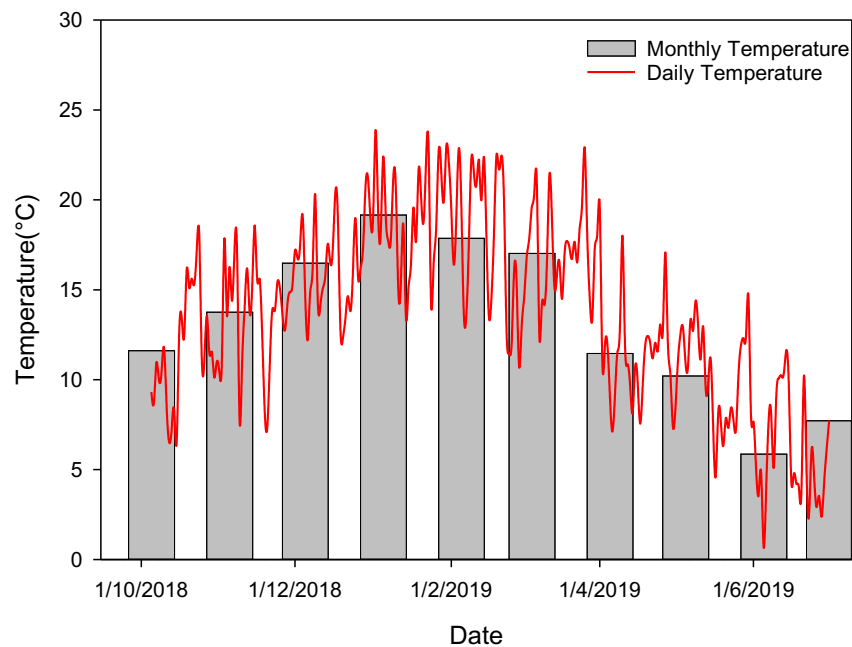


Figure 4.1 Mean monthly (solid bar) and daily (red line) air temperatures from October 2018 to July 2019 measured at the Broadfields Metereological Station (Lincoln, New Zealand).

4.1.2 Soil Moistures

Soil moistures (120 mm) ranged from 16%-33%, from October 2018 to July 2019 across treatments (Figure 4.2) (complete ANOVA results can be found in appendix 1). There were no significant differences across treatments. The highest and lowest soil moisture contents occurred in December 2018 (33.1%) and February 2019 (16.1%), respectively.

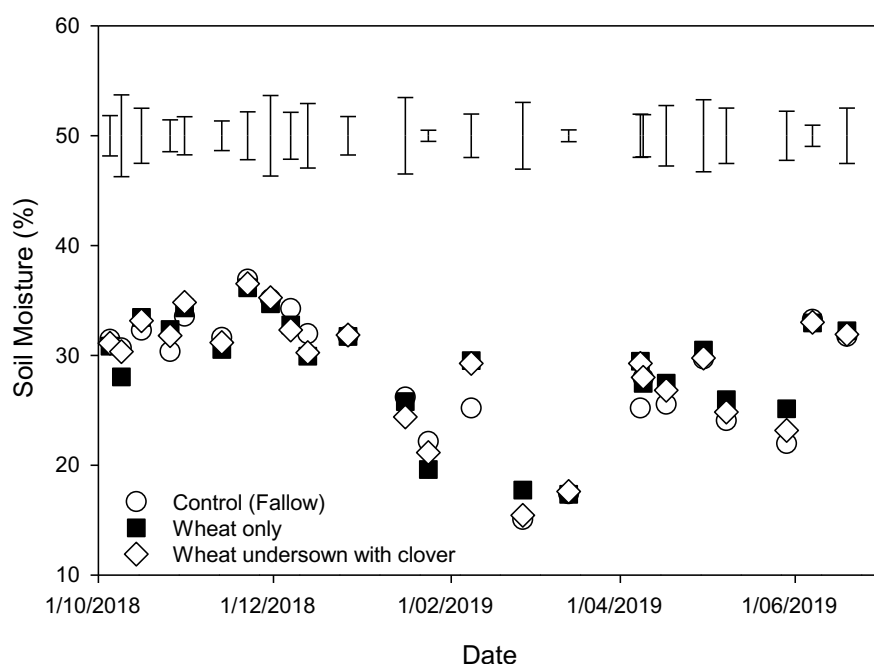


Figure 4.2 Soil moisture (120 mm) measured from the intercropped treatments (\diamond = wheat undersown with clover, \blacksquare = wheat only and \circ = control (Fallow)) from October 2018 to July 2019. Bars represent half of pooled $LSD_{\alpha=0.05}$ of the treatments means for each sampling date. ANOVA results can be found in appendix 1.

4.1.3 Available Radiation for Wheat

A Gaussian, 3 parameter fitted curve ($R^2 = 0.79$) showed that available radiation (MJ/m^2) for wheat intercropped with olive trees (green line) was lower than the total solar radiation in Canterbury (red line) during the whole year (Figure 4.3). Both increased from July 2018 and reached a peak on January 2019 then decreased until July 2019. In January, the available radiation for wheat intercropped with olive (15 MJ/m^2) was approximately 25% lower than the total solar radiation in Canterbury (20 MJ/m^2).

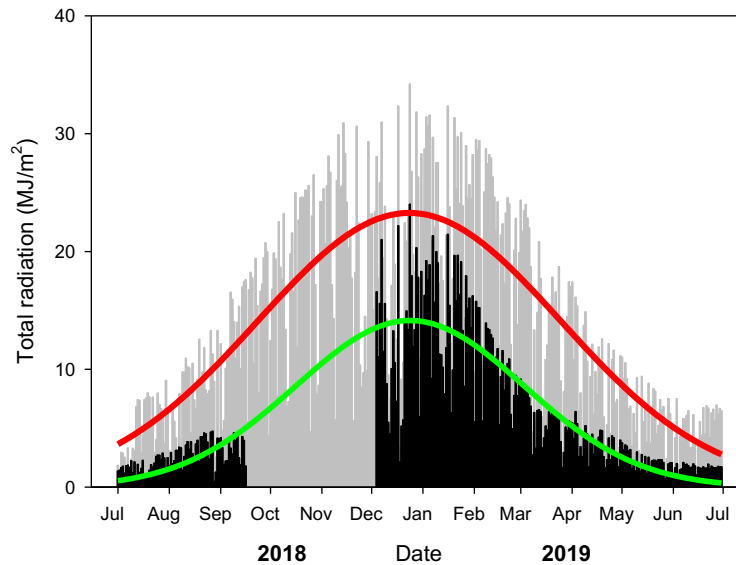


Figure 4.3 Available radiation for wheat intercropped with olive trees from July 2018 to July 2019. The red line ($R^2 = 0.86$) fitted to the total available radiation in Canterbury recorded from Broadfield Meteorological Station, Lincoln. The green line $R^2 = 0.79$ fitted to the total available radiation for wheat intercropped with olive trees recorded by two line quantum sensors placed in the olive grove. As the quantum sensors were not placed until December 2018, data from July 2019 to September 2019 were used in place of July 2018 to September 2018 period. Available radiation for wheat from October 2018 to November 2018 was not recorded.

4.2 Olive Trees

4.2.1 Shoot Length

There was no significant difference ($P > 0.05$) in maximum olive shoot length across the intercropping treatments. However, there was a significant difference ($P < 0.05$) among olive cultivars (Table 4.1). Mean maximum shoot length of Leccino was 23.4 cm, and Barnea and Frantoio both averaged 17.3 cm. The thermal-times to maximum shoot length and growth rate were similar across all treatments (all $P > 0.05$). The mean thermal-times, measured from wheat crop emergence, until maximum shoot length, was 1182 °Cd and shoot growth rate was 0.01 cm/°Cd across all treatments.

A broken stick model was fitted to shoot length against thermal-time (measured from wheat emergence) as shown in Figure 4.4. The model explained 98% of the data variation. Olive shoot growth stopped at 1182 °Cd (January 2019) for all treatments. This is shown by the breaking point of the model (Figure 4.4). Maximum shoot length of Leccino was higher than that of Barnea and Frantoio.

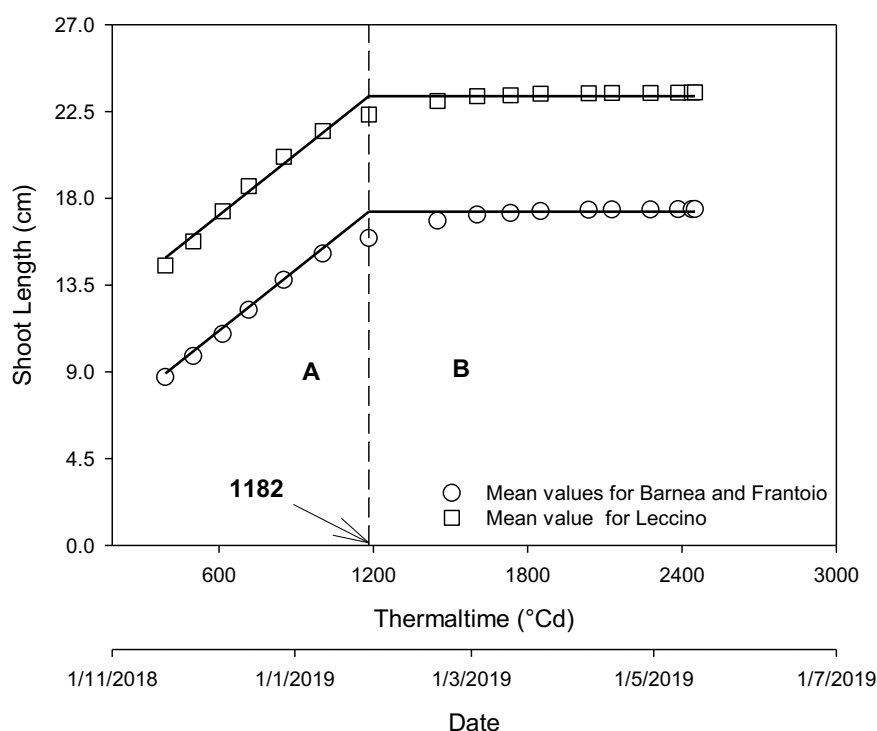


Figure 4.4 Mean shoot length against thermal-time of Barnea and Frantoio combined data (○) and Leccino (□) from November 2018 to July 2019. Broken stick models were fitted to the data and the breaking point, when the slope of the linear curve changes is indicated by the dashed line. Phase A refers to shoot length increasing, phase B refers to maximum shoot length phase. Regressions A (before the breaking point) and B (after the breaking point) are: 'Leccino': A: $y = 0.0103x + 10.892$, B: $y = 23.1$; $R^2 = 0.98$; 'Barnea & Frantoio': A: $y = 0.096x + 5.16$, B: $y = 16.5$; $R^2 = 0.98$. Dates are displayed for reference.

Table 4.1 Maximum Shoot lengths (SL) and Thermal-times (Tt) and growth rates for Barnea, Frantoio and Leccino for three treatments from November 2018 to July 2019. W = wheat only. W/C = wheat undersown with Clover. C = Control (Fallow). LSD = Least significant difference. Significant difference is shown in bold type.

| Cultivar | Treatment | Maximum SL(cm) | Maximum Tt(°Cd) | Growth Rate |
|---|-----------|----------------|-----------------|-------------|
| Barnea | C | 14.8 | 1279 | 0.01 |
| Barnea | W | 18.4 | 1321 | 0.01 |
| Barnea | W/C | 18.6 | 1106 | 0.01 |
| Mean | | 17.3 | 1235 | 0.01 |
| Frantoio | C | 17.8 | 1307 | 0.01 |
| Frantoio | W | 17.0 | 1194 | 0.01 |
| Frantoio | W/C | 17.4 | 1122 | 0.01 |
| Mean | | 17.4 | 1208 | 0.01 |
| Leccino | G | 23.8 | 1221 | 0.13 |
| Leccino | W | 23.9 | 1094 | 0.13 |
| Leccino | W/C | 22.4 | 995 | 0.10 |
| Mean | | 23.4 | 1103 | 0.01 |
| $P_{\text{treatment } \alpha=0.05}$ | | 0.97 | 0.27 | 0.82 |
| $P_{\text{cultivar } \alpha=0.05}$ | | 0.04 | 0.27 | 0.82 |
| $P_{\text{treatment} * \text{cultivar } \alpha=0.05}$ | | 0.90 | 0.90 | 0.59 |
| LSD $\alpha=0.05$ | | 5.33 | 392 | 0.09 |

4.2.2 Number of Leaves

There were no significant differences in olive leaf appearance and leaf abscission rates across all treatments ($P > 0.05$) (Table 4.2). Similarly, there were no significant differences in maximum number of leaves and thermal-time to maximum number of leaves across all treatments ($P > 0.05$).

The broken stick model fitted to the mean leaf number of the three olive tree cultivars against thermal-time ($R^2 = 0.88$) (Figure 4.5) shows that the number of leaves increased at a rate of 0.01 leaves/ $^{\circ}\text{Cd}$ until the 20/01/2019 (1118 $^{\circ}\text{Cd}$) and then decreased at a rate of 0.003 leaves/ $^{\circ}\text{Cd}$. The number of leaves reached their peak (23) at 1118 $^{\circ}\text{Cd}$.

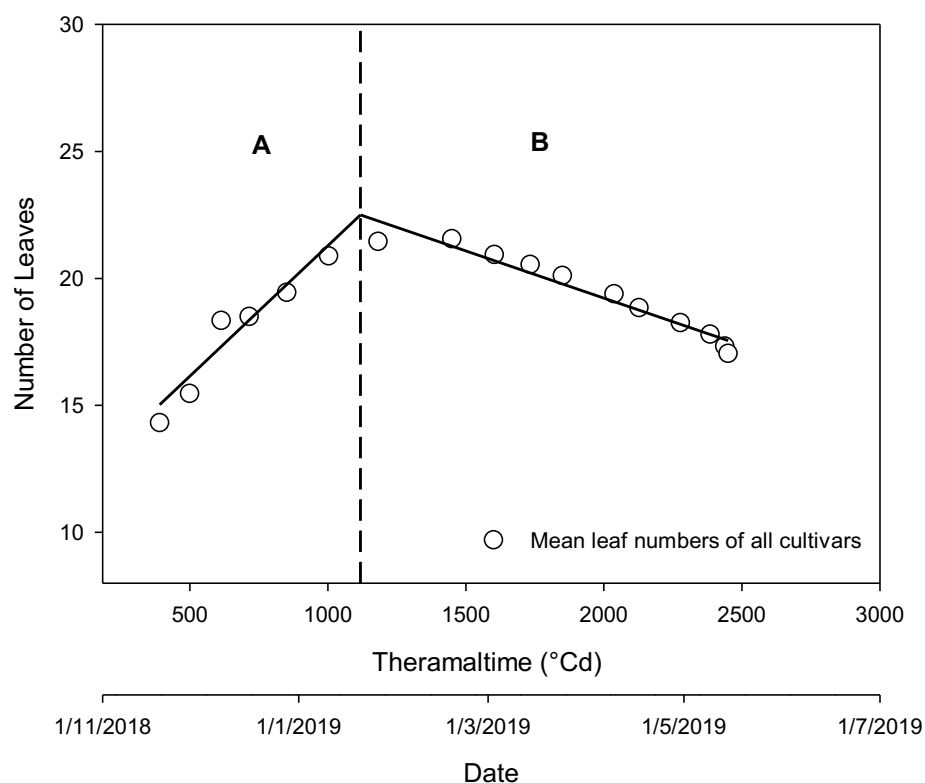


Figure 4.5 Mean number of leaves of three olive tree cultivars (Barnea, Frantoio and Leccino) measured on labelled stems against thermal-time (Tt) from November 2018 to July 2019. A broken stick model was fitted to the data. The breaking point of the model, when the slope of the linear curve changed is indicated by the dashed line (1118 $^{\circ}\text{Cd}$). During phase A, growth was linear and increasing, whereas in phase B leaf numbers decreased. The model's parameters are: A (before the breaking point) $y=0.0103x+11$; $R^2= 0.88$; and B (after the breaking point) $y=-0.003734x+26.6981$; $R^2=0.88$. Dates are displayed for reference.

Table 4.2 Leaf appearance and abscission rates, maximum number of leaves and thermal-time (Tt) of maximum number of leaves for three cultivars (Barnea, Frantoio and Leccino) for different treatments (W = wheat only. W/C = wheat undersown with clover. C = Control (Fallow) from November 2018 to July 2019. LSD = Least significant difference.

| Cultivar | Treatment | Rate of leaf appearance (leaf/°Cd) | Maximum number of Leaves | Maximum leaf number Tt (°Cd) | Rate of leaf abscission (leaf/°Cd) |
|------------------------------------|-----------|------------------------------------|--------------------------|------------------------------|------------------------------------|
| Barnea | C | 0.01 | 25.2 | 1306 | -0.01 |
| Barnea | W | 0.01 | 19.6 | 1156 | -0.003 |
| Barnea | W/C | 0.02 | 31.4 | 1158 | -0.01 |
| Mean | | 0.01 | 25.4 | 1207 | -0.01 |
| Frantoio | C | 0.01 | 19.2 | 1413 | -0.01 |
| Frantoio | W | 0.01 | 19.7 | 1230 | -0.004 |
| Frantoio | W/C | 0.01 | 17.2 | 1126 | -0.001 |
| Mean | | 0.01 | 18.7 | 1256 | -0.003 |
| Leccino | C | 0.01 | 25.2 | 1172 | 0.004 |
| Leccino | W | 0.01 | 24.5 | 1093 | -0.004 |
| Leccino | W/C | 0.01 | 22.4 | 1082 | -0.002 |
| Mean | | 0.01 | 24 | 1116 | -0.001 |
| P treatment $\alpha=0.05$ | | 0.954 | 0.71 | 0.441 | 0.385 |
| P cultivar $\alpha=0.05$ | | 0.128 | 0.27 | 0.189 | 0.099 |
| P treatment*cultivar $\alpha=0.05$ | | 0.789 | 0.62 | 0.84 | 0.308 |
| LSD | | 0.01 | 13.8 | 371 | 0.01 |

4.2.3 Chlorophyll Concentration during the Growing Season

Based on the SPAD readings obtained and their corresponding chlorophyll concentration (Inskeep & Bloom, 1985) (Table 4.3), the following equation models were produced:

Equation 7 Barnea: $y = (7.389 \cdot x) - 72.02$; $R^2 = 0.98$

Equation 8 Frantoio: $y = (9.673 \cdot x) - 249.5$; $R^2 = 0.96$

Equation 9 Leccino: $y = (8.772 \cdot x) - 182.6$; $R^2 = 0.92$

where y = chlorophyll concentration, x = SPAD reading

Table 4.3 SPAD readings and corresponding chlorophyll concentrations as determined by the DMF chlorophyll method, and using equations from Inskeep and Bloom (1985), for three olive tree cultivars (Barnea, Frantoio, Leccino) (Fitted lines can be found in Appendix 3)

| Cultivar | SPAD Range | SPAD | Total chlorophyll Concentration (mg/m ²) |
|----------|------------|------|--|
| Barnea | 26.8-33.8 | 32.5 | 91 |
| Barnea | 33.8-40.8 | 39.8 | 116 |
| Barnea | 40.8-47.8 | 44.1 | 222 |
| Barnea | 47.8-54.8 | 50.5 | 304 |
| Barnea | 54.8-61.8 | 57.5 | 373 |
| Barnea | 61.8-68.8 | 63.1 | 347 |
| Barnea | 68.8-75.8 | 71.9 | 453 |
| Barnea | 75.8-78.7 | 77.8 | 479 |
| Frantoio | 31.7-38.7 | 36.6 | 150 |

| | | | |
|----------|-----------|------|-----|
| Frantoio | 38.7-45.7 | 43.1 | 214 |
| Frantoio | 45.7-52.7 | 46.1 | 278 |
| Frantoio | 52.7-59.7 | 53.8 | 313 |
| Frantoio | 59.7-66.7 | 61.4 | 356 |
| Frantoio | 66.7-73.7 | 67.0 | 401 |
| Frantoio | 73.7-80.7 | 75.1 | 430 |
| Frantoio | 80.7-88.3 | 87.2 | 513 |
| Leccino | 25.2-32.2 | 34.8 | 141 |
| Leccino | 32.2-39.2 | 37.7 | 171 |
| Leccino | 39.3-46.2 | 44.9 | 206 |
| Leccino | 46.2-53.2 | 49.3 | 248 |
| Leccino | 53.2-60.2 | 56.1 | 311 |
| Leccino | 60.2-67.2 | 66.4 | 379 |
| Leccino | 67.2-74.2 | 72.5 | 441 |
| Leccino | 74.2-80.4 | 76.7 | 655 |

There were no significant difference in chlorophyll concentration across intercropping treatments ($P > 0.05$) (Table 4.4). The broken stick models fitted to the chlorophyll concentrations of the three olive tree cultivars against thermal-time (R^2 ranged from 0.90 to 0.97) (Figure 4.6). The chlorophyll concentration of all three cultivars decreased ($P > 0.05$) (Table 4.4) during Phase A at the same rate. After the lowest point on the 12/01/2019 (1017 °Cd), the chlorophyll concentration increased, with Frantoio having the fastest rate of increase and Leccino the lowest ($P = 0.006$) (Table 4.4).

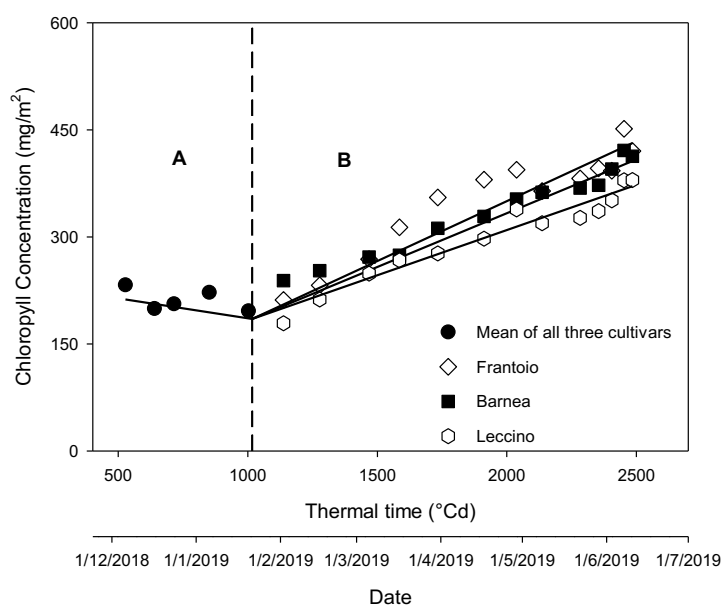


Figure 4.6 Chlorophyll concentration for three olive tree cultivars (Barnea, Frantoio, Leccino) against thermal-time from December 2018 to July 2019. Concentrations were calculated by Equation 7 Barnea: $y = (7.389 \cdot x) - 72.02$; $R^2 = 0.98$; Equation 8 Frantoio: $y = (9.673 \cdot x) - 249.5$; $R^2 = 0.96$; Equation 9 Leccino: $y = (8.772 \cdot x) - 182.6$; $R^2 = 0.92$. Broken stick models were fitted to these data. The break point of the model, when the slope of the linear curves changed, is indicated by the dashed line (1017 °Cd). Parameters are shown in Table 4.4 for the equation parameters. R^2 ranges from 0.90 to 0.97. Dates are displayed for reference.

Table 4.4 Rates of chlorophyll concentration for the model phase A and phase B, Breaking point of chlorophyll concentration and thermal-time (Tt) for three olive tree cultivars (Barnea, Frantoio, Leccino) across different intercropping treatments (W = wheat only. W/C = wheat undersown with clover. C = control (Fallow) from December 2018 to July 2019. LSD = Least significant difference. Significant difference is shown in bold type.

| Cultivar | Treatment | Model phase A rate (mg/m ²⁰ Cd) | Breaking point chlorophyll concentration (mg/m ²) | Breaking point Tt(°Cd) | Model phase B rate(mg/m ²⁰ Cd) |
|------------------------------------|-----------|--|---|------------------------|---|
| Barnea | C | -0.06 | 205 | 982 | 0.16 |
| Barnea | W | -0.08 | 186 | 1260 | 0.15 |
| Barnea | W/C | -0.14 | 244 | 1288 | 0.16 |
| Mean | | -0.09 | 212 | 1177 | 0.16 |
| Frantoio | C | -0.03 | 179 | 913 | 0.16 |
| Frantoio | W | -0.13 | 178 | 755 | 0.16 |
| Frantoio | W/C | -0.25 | 137 | 971 | 0.23 |
| Mean | | -0.14 | 165 | 880 | 0.18 |
| Leccino | C | -0.09 | 167 | 997 | 0.12 |
| Leccino | W | -0.11 | 161 | 920 | 0.14 |
| Leccino | W/C | -0.05 | 205 | 1063 | 0.12 |
| Mean | | -0.09 | 178 | 993 | 0.13 |
| P treatment $\alpha=0.05$ | | 0.60 | 0.70 | 0.61 | 0.37 |
| P Cultivar treatment $\alpha=0.05$ | | 0.76 | 0.21 | 0.12 | 0.006 |
| P Cultivar*Treatment $\alpha=0.05$ | | 0.71 | 0.50 | 0.72 | 0.09 |
| LSD | | 0.28 | 90.8 | 511 | 0.03 |

4.2.4 Stomatal Conductance

There was no significant difference in stomatal conductance produced by the intercropping treatments ($P > 0.05$). However, there was a significant difference among cultivars on some days (e.g. 15/12/2018, 30/01/2019 and 12/02/2019) (complete ANOVA results can be found in appendix 2). Before 1017 °Cd, stomatal conductance fluctuated between 196 and 417 (mol/m²s)(Figure 4.7); after the 1017 °Cd (12/01/2019), all cultivars showed a decreased in stomatal conductance from 400 to 160 (mol/m²s).

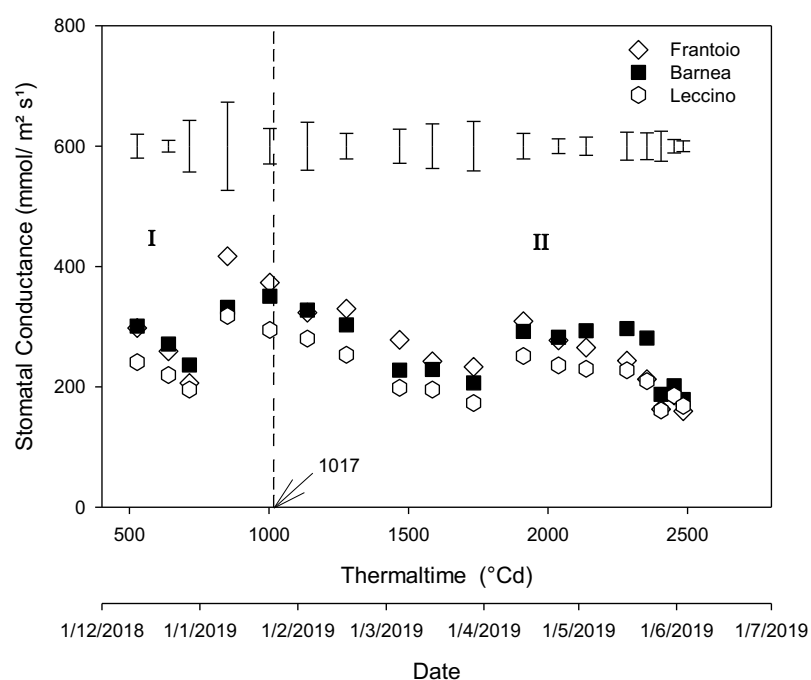


Figure 4.7 Stomatal conductance for three olive tree cultivars (Barnea, Frantoio and Leccino) against thermal-time from December 2018 to July 2019. Bars represent the half of pooled $LSD_{\alpha=0.05}$ of the treatments means for each sampling date. The dashed line, displayed for reference, is the time at which the chlorophyll concentration changed (see Figure 4.6). Dates are displayed for reference. The ANOVA results of stomatal conductance can be found in appendix 2.

4.2.5 Fresh Matter, Dry Matter and Chlorophyll Concentration of Harvested Leaves

There was no significant difference in fresh matter and dry matter leaf weights and chlorophyll concentration across intercropping treatments (all $P > 0.05$). There were significant differences in fresh matter ($P = 0.003$) and dry matter ($P = 0.005$) leaf weights among cultivars (Table 4.5). Leccino had the highest fresh leaf weight and dry matter leaf weight (0.24 g/leaf and 0.11 g/leaf, respectively). Chlorophyll concentrations were highly significantly different among cultivars ($P < 0.001$) with Leccino having the lowest concentration (417 mg/kg) and Frantoio the highest (484 mg/kg).

Table 4.5 Fresh, dry matter and chlorophyll concentrations of leaves of three olive tree cultivars (Barnea, Frantoio and Leccino) with three intercropping treatments (W = wheat only. W/C = wheat undersown with clover. C = control (fallow)). Chlorophyll concentrations were calculated using the equations from section 4.2.3. LSD = Least significant difference. Significant differences are shown in bold type.

| Cultivar | Treatment | Fresh Matter (g/leaf) | Dry Matter (g/leaf) | Chlorophyll Concentration (mg/m ²) |
|----------|-----------|-----------------------|---------------------|--|
| Frantoio | C | 0.22 | 0.11 | 449 |
| Frantoio | W | 0.21 | 0.10 | 516 |
| Frantoio | W/C | 0.19 | 0.09 | 486 |

| | | | | |
|---|-----|--------------|--------------|-----------------|
| Mean | | 0.21 | 0.10 | 484 |
| Leccino | C | 0.25 | 0.12 | 407 |
| Leccino | W | 0.25 | 0.12 | 423 |
| Leccino | W/C | 0.21 | 0.10 | 420 |
| Mean | | 0.24 | 0.11 | 417 |
| Barnea | C | 0.19 | 0.10 | 455 |
| Barnea | W | 0.19 | 0.09 | 456 |
| Barnea | W/C | 0.18 | 0.10 | 448 |
| Mean | | 0.19 | 0.10 | 453 |
| P _{Treatment} $\alpha=0.05$ | | 0.14 | 0.13 | 0.17 |
| P _{Cultivar} $\alpha=0.05$ | | 0.003 | 0.005 | <.001 |
| P _{Cultivar*Treatment} $\alpha=0.05$ | | 0.67 | 0.59 | 0.12 |
| LSD $\alpha=0.05$ | | 0.025 | 0.010 | 20.6 |

4.2.6 Leaf Protein and Mineral Contents

There was no significant difference in protein content for all treatments ($P > 0.05$) (Table 4.6) and this averaged 9.93%. There were also no significant differences in Al, Ca, Cr, Cu, Mg, Mn and Zn contents among cultivars ($P > 0.05$). There was a significant cultivar difference in Fe content ($P < 0.05$) and highly significant differences in K, Mo, Na, P and S contents ($P \leq 0.001$). Barnea and Leccino had the highest (98.9 mg/kg) and lowest (65.1 mg/kg) Fe contents, respectively. However, as showed in Table 4.6, the K, Mo, Na, P, and S contents of Barnea were all lower than that of Frantoio and Leccino. The highest content of K was found in Frantoio and Leccino had the highest content of Mo, Na, P and S.

Table 4.6 Protein and mineral element contents of leaves of three olive tree cultivars (Barnea, Frantoio and Leccino) with three intercropping treatments (W = wheat only. W/C = wheat undersown with clover. C = control (fallow)). *LSD* = Least significant difference. *Al* = aluminium; *Ca* = Calcium; *Cr* = Chromium; *Cu* = Copper; *Fe* = Iron; *K* = Potassium; *Mg* = Magnesium; *Mn* = Manganese; *Mo* = Molybdenum; *Na* = Sodium; *P* = Phosphorus; *S* = Sulphur; *Zn* = Zinc. Protein content = 6.25*N%. Significant differences are shown in bold type.

| Cultivar | Treatment | Protein Content (%) (6.25*N%) | Al (mg/kg) | Ca (mg/kg) | Cr (mg/kg) | Cu (mg/kg) | Fe (mg/kg) | K (mg/kg) | Mg (mg/kg) | Mn (mg/kg) | Mo (mg/kg) | Na (mg/kg) | P (mg/kg) | S (mg/kg) | Zn (mg/kg) |
|--|-----------|----------------------------------|---------------|---------------|---------------|---------------|---------------|-----------------|---------------|---------------|-----------------|-----------------|-----------------|--------------|---------------|
| Frantoio | C | 9.91 | 33.2 | 10618 | 0.462 | 11.1 | 76.2 | 10930 | 1019 | 21.7 | 0.165 | 209 | 1927 | 1585 | 16.7 |
| Frantoio | W | 10.3 | 27.3 | 10132 | 0.319 | 11.3 | 76.0 | 10795 | 888 | 19.7 | 0.198 | 178 | 1714 | 1499 | 17.5 |
| Frantoio | W/C | 10.3 | 34.3 | 11441 | 0.578 | 13.1 | 86.9 | 11524 | 1093 | 24.6 | 0.247 | 160 | 1785 | 1613 | 19.5 |
| Mean | | 10.2 | 31.6 | 10731 | 0.453 | 11.8 | 79.7 | 11083 | 1000 | 22.0 | 0.203 | 182 | 1809 | 1566 | 17.9 |
| Leccino | C | 9.65 | 31.7 | 11541 | 0.430 | 10.4 | 67.1 | 9877 | 1025 | 23.5 | 0.267 | 271 | 2115 | 1674 | 15.6 |
| Leccino | W | 9.58 | 28.1 | 11198 | 0.262 | 10.1 | 57.2 | 10395 | 1011 | 22.9 | 0.180 | 249 | 2255 | 1697 | 15.5 |
| Leccino | W/C | 10.3 | 30.4 | 9738 | 0.425 | 13.3 | 71.1 | 9244 | 939 | 22.8 | 0.282 | 262 | 2255 | 1721 | 19.6 |
| Mean | | 9.85 | 30.0 | 10826 | 0.372 | 11.3 | 65.1 | 9839 | 992 | 23.1 | 0.243 | 261 | 2208 | 1697 | 16.9 |
| Barnea | C | 9.74 | 27.3 | 10374 | 0.284 | 12.1 | 104 | 6546 | 932 | 27.7 | 0.108 | 161 | 1646 | 1563 | 16.8 |
| Barnea | W | 9.77 | 26.4 | 10396 | 0.144 | 11.9 | 100 | 6360 | 932 | 29.0 | 0.143 | 113 | 1870 | 1504 | 14.7 |
| Barnea | W/C | 9.73 | 29.3 | 10671 | 0.439 | 12.3 | 93.2 | 6404 | 938 | 29.8 | 0.135 | 82.7 | 1911 | 1507 | 14.7 |
| Mean | | 9.74 | 27.7 | 10480 | 0.289 | 12.1 | 98.9 | 6437 | 934 | 28.8 | 0.129 | 119 | 1809 | 1525 | 15.4 |
| P _{treatment} α=0.05 | | 0.753 | 0.563 | 0.731 | 0.055 | 0.395 | 0.588 | 0.936 | 0.716 | 0.77 | 0.819 | 0.435 | 0.804 | 0.855 | 0.65 |
| P _{Cultivar} α=0.05 | | 0.320 | 0.140 | 0.781 | 0.438 | 0.694 | 0.007 | <.001 | 0.401 | 0.084 | <.001 | <.001 | <.001 | 0.001 | 0.235 |
| P _{Cultivar*Treatment} α=0.05 | | 0.719 | 0.723 | 0.206 | 0.985 | 0.724 | 0.805 | 0.775 | 0.304 | 0.952 | 0.126 | 0.476 | 0.135 | 0.531 | 0.475 |
| LSD | | 1.30 | 10.6 | 1684.6 | 0.398 | 4.11 | 18.7 | 1307.7 | 209 | 10.6 | 0.047 | 32.4 | 155 | 78.6 | 6.51 |

4.3 Clover

4.3.1 Final Yield

Although no clover was sown in the plot with wheat only, volunteer clover appeared in these plots. The fresh matter yield of clover from W/C (wheat undersown with white clover) treatments was significantly higher ($P = 0.02$) than the W (wheat only plots) treatment (Table 4.7). There was also a significant difference in dry matter yield of these two treatments ($P = 0.04$).

Table 4.7 Fresh matter and dry matter of white clover (*Trifolium repens*) after harvesting from W (wheat only) and W/C (wheat undersown with clover). LSD = Least significant difference. Significant differences are shown in bold type. NB: clover in the wheat only plots was from volunteer plants.

| Treatment | Fresh Matter (g/m ²) | Dry Matter (g/m ²) |
|-------------------|-------------------------------------|-----------------------------------|
| W | 31.5 | 6.50 |
| W/ C | 147 | 27.5 |
| P $\alpha=0.05$ | 0.02 | 0.04 |
| LSD $\alpha=0.05$ | 76.9 | 18.6 |

4.4 Wheat

4.4.1 Wheat Emergence

The thermal-times, measured from after planting and the final plant population (m²) for the two treatments are shown in Table 4.8. No significant differences were recorded between treatments ($P > 0.05$). The milling wheat crop reached 100% emergence (334 plants/m²) after 79.9 °Cd and 15.5 days regardless of the intercropping treatment applied.

Table 4.8 Thermal-time and days after planting (DAP) to reach 100% emergence of wheat for treatments (W = wheat only. W/C = wheat undersown with clover) from September to October 2018. LSD = Least significant difference.

| Treatment | DAP | Thermal-time (°Cd) | Number of plants (m ²) |
|-------------------|------|--------------------|------------------------------------|
| W | 15.7 | 80.6 | 403 |
| W/C | 15.3 | 79.1 | 264 |
| Mean | 15.5 | 79.9 | 334 |
| P $\alpha=0.05$ | 0.42 | 0.42 | 0.11 |
| LSD $\alpha=0.05$ | 1.43 | 6.35 | 210 |

4.4.2 Wheat Canopy Ground Cover

A Piece-wise curves fitted model ($R^2 = 0.99$) shows that canopy ground cover against thermal-time after full emergence occurred in three phases of growth (Figure 4.8). Both treatments (W and W/C) had similar canopy ground cover changes ($P > 0.05$) (Table 4.9). The phase of canopy expansion from full emergence until maximum ground cover (0.88/88%) lasted for 321 °Cd (Table 4.9). The maximum canopy ground cover lasted 487 °Cd and declined until harvest.

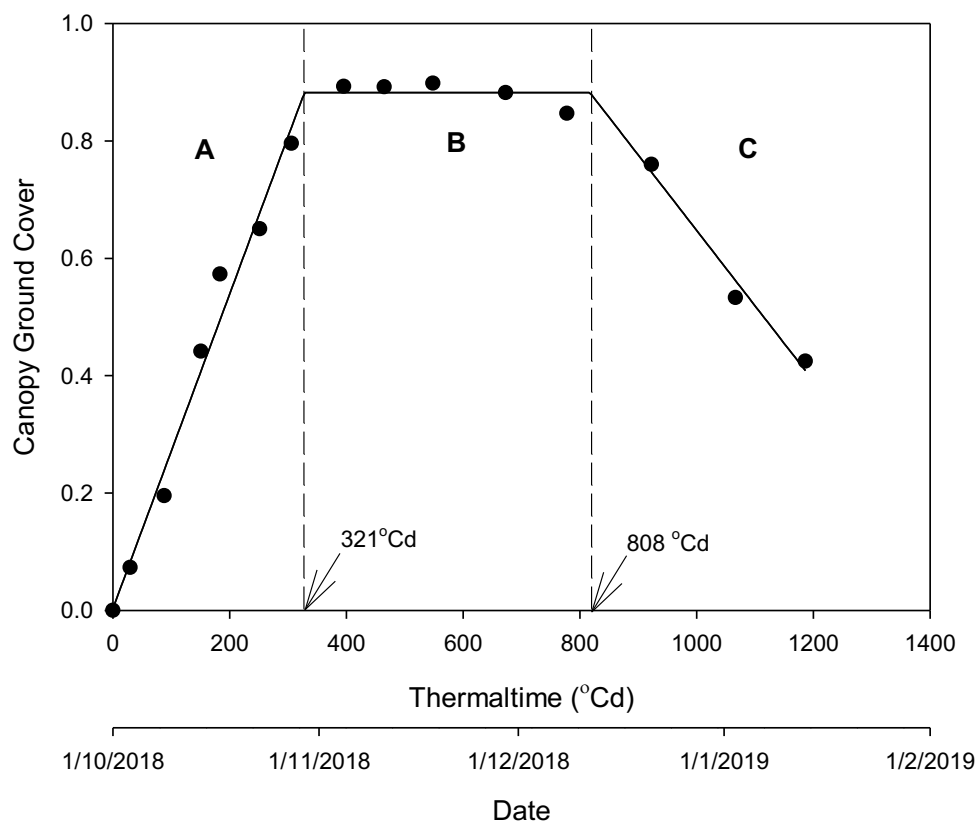


Figure 4.8 Mean wheat canopy ground cover from treatments (W = wheat only. W/C = wheat and clover) (●) and Piece-wise curves fitted model ($R^2 = 99\%$) (Black Line) after full emergence against thermal-time during the growing season (from October 2018 to January 2019). Dashed lines indicate the canopy ground cover changes during the wheat's development. Phase A refers to canopy ground cover increasing, phase B is maximum canopy ground cover from 321 °Cd to 808 °Cd. Phase C refers to maximum canopy ground cover decreasing. Dates are displayed for reference.

Table 4.9 Canopy ground cover changes for treatments (W = wheat only. W/C = wheat undersown with clover) after full emergence from October 2018 to January 2019. LSD = Least significant difference.

| Treatment | Max Canopy Ground Cover | Thermal-time to Max Canopy Ground Cover (°Cd) | Duration of constant phase (°Cd) |
|-------------------|-------------------------|---|----------------------------------|
| W | 0.88 | 325 | 459 |
| W/C | 0.88 | 317 | 515 |
| Mean | 0.88 | 321 | 487 |
| P $\alpha=0.05$ | 0.57 | 0.80 | 0.49 |
| LSD $\alpha=0.05$ | 0.07 | 117 | 285 |

4.4.3 Wheat Final Yields

Final wheat yields are shown in Table 4.10. There was no difference between the two different intercropping treatments ($P > 0.05$). On average the milling wheat produced 278 ears/m² and 34 grains/ear. The 1000 grain wheat and total grain weight was 36.6 g and 285 g/m², respectively.

Table 4.10 Numbers of ears, grains/ear and 1000 grain weight (TGW), total grains weight for W (wheat only) and W/C (wheat undersown with clover) plots. LSD = Least significant difference

| Treatment | Numbers of Ears/m ² | Numbers of Grains/ears | TGW (g) | Total Grain Weight/m ² (g) |
|-------------------|--------------------------------|------------------------|---------|---------------------------------------|
| W | 300 | 32 | 35.6 | 316 |
| W/C | 257 | 35 | 37.5 | 254 |
| Mean | 278 | 34 | 36.6 | 285 |
| P $\alpha=0.05$ | 0.27 | 0.09 | 0.18 | 0.09 |
| LSD $\alpha=0.05$ | 126 | 3.8 | 3.98 | 19.9 |

4.4.4 Wheat Grain Nutrients Analysis

Table 4.11 shows the crude protein and mineral element contents of the two intercropping treatments (W = wheat only. W/C = wheat undersown with clover) were not significantly different (all $P > 0.05$). For both treatments, mean crude protein content was 14.2 %.

Table 4.11 Crude protein and mineral element contents of wheat from *W* (wheat only) and *W/C* (wheat undersown with clover). Crude protein = 6.25*N%. LSD = Least significant difference. ns = not significant.

| Treatment | Crud protein (%) (6.25*N%) | Phosphorus (%) | Potassium (%) | Sulphur (%) | Calcium (%) | Magnesium (%) | Iron (mg/kg) | Manganese (mg/kg) | Zinc (mg/kg) | Copper (mg/kg) |
|-----------------------|-------------------------------|-------------------|------------------|----------------|----------------|------------------|-----------------|----------------------|-----------------|-------------------|
| W | 14.1 | 0.40 | 0.50 | 0.14 | 0.02 | 0.14 | 26.3 | 24.3 | 36.7 | 5.67 |
| W/C | 14.2 | 0.40 | 0.53 | 0.14 | 0.03 | 0.14 | 27.3 | 25.3 | 39.3 | 5.67 |
| Mean | 14.2 | 0.40 | 0.52 | 0.14 | 0.03 | 0.14 | 26.8 | 24.8 | 38.0 | 5.67 |
| P _{α=0.05} | 0.7 | 0.69 | 0.42 | 0.42 | 0.18 | ns | 0.23 | 0.23 | 0.21 | 1 |
| LSD _{α=0.05} | 1.62 | 0.06 | 0.14 | 0.014 | 0.01 | ns | 2.48 | 2.48 | 6.25 | 2.48 |

4.5 Phenology Calendar of Olive Trees and Wheat

The shoot elongation phase of the olive trees lasted approximately one month after the wheat reached its maximum canopy ground cover. Also, the number of olive leaves reached its maximum number on January, and reproductive development (including flowering) followed (Figure 4.9).

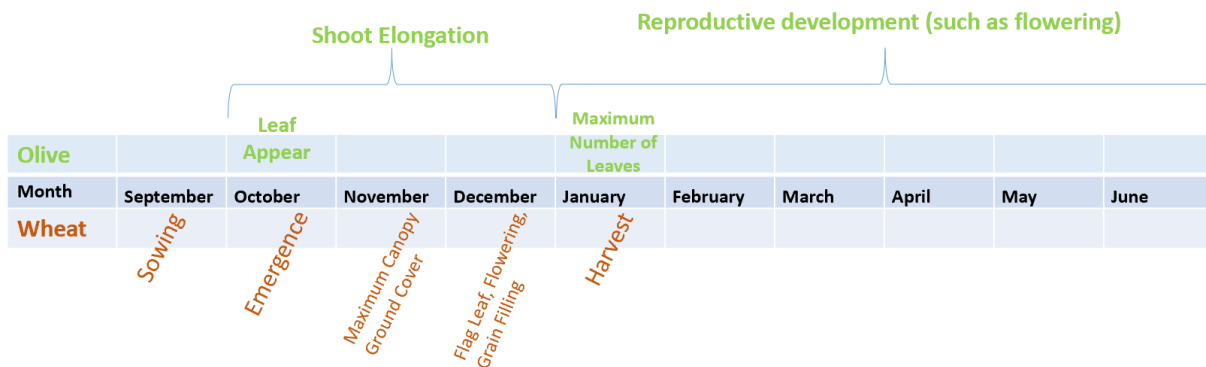


Figure 4.9 Phenology calendar of olive trees (top) and wheat (bottom).

4.6 Sensitivity Analysis

4.6.1 Different Wheat Canopy/Phenology Models

The wheat canopy/phenology models, fitted for the actual sowing date (20/9/2018)/eight models derived from additional simulated sowing dates as described in section 3.8 are showed in Figure 4.10. This figure also includes the available radiation for wheat intercropped with olives. The following sections describe how the different sowing dates influence on crop emergence, number of days to maximum canopy ground cover, number of days from full emergence to harvest, wheat total available radiation intercepted and available radiation at flag leaf in an olive wheat intercropping system.

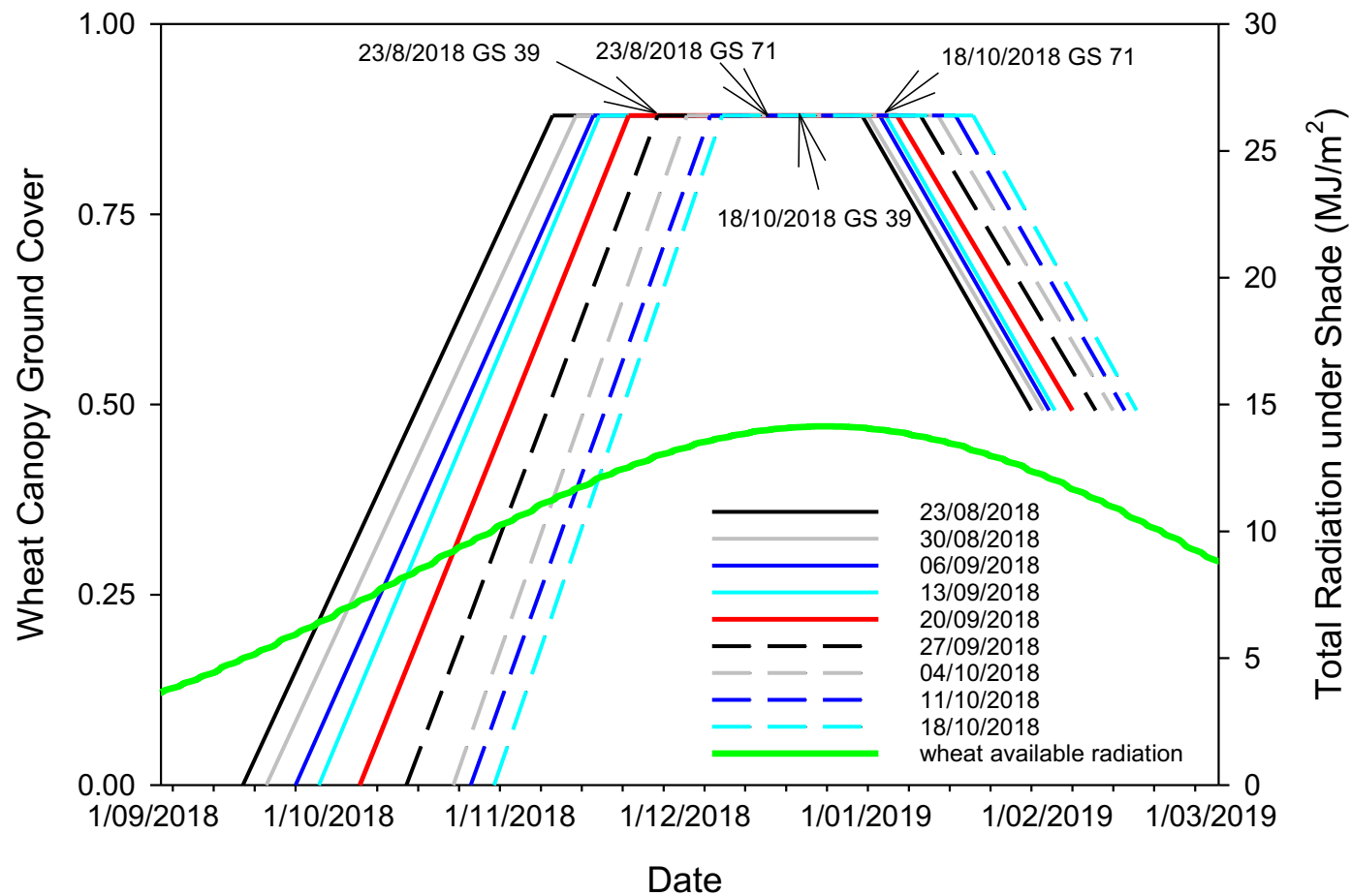


Figure 4.10 Nine wheat growth models created as described in section 3.8 and based on the parameters in Table 4.12. Lines represent sowing on 20/9/2018 (red line), 23/8/2018 (black line), 30/8/2018 (grey line), 06/9/2018 (blue line), 13/9/2018 (light blue line), 27/9/2018 (black dotted line), 4/10/2018 (grey dotted line), 11/10/2018 (blue dotted line) and 18/10/2018 (light blue dotted line). The arrow indicates the time of flag leaf emergence (grow stage (GS) 39) and grain development (GS 71) of wheat sown on 23/8/2018 and 18/10/2018. Green line represents the available radiation for wheat intercropped with olive trees.

Table 4.12 Parameters for creating canopy/phenology models of different simulated wheat sowing dates. Number of days from full emergence to maximum canopy ground cover (CGC), number of day of constant phase last and number of days from emergence to harvest were estimated by the thermal-time. Date for full emergence, maximum CGC, harvest, flag leaf emergence (GS 39), anthesis (GS 61) and grain development (GS 71). Number of days = NOD

| Sowing date | NOD to full emergence | Full emergence date | NOD to Max CGC | Max CGC date | NOD of constant Phase last | End of constant phase date | NOD from emergence to Harvest | Harvest date | Flag leaf emergence (GS 39) | Anthesis (GS 61) | Grain Development (GS 71) |
|-------------|-----------------------|---------------------|----------------|--------------|----------------------------|----------------------------|-------------------------------|--------------|-----------------------------|------------------|---------------------------|
| 23/08/2018 | 23 | 15/09/2018 | 53 | 7/11/2018 | 53 | 30/12/2018 | 135 | 28/01/2019 | 25/11/2018 | 5/12/2018 | 19/12/2018 |
| 30/08/2018 | 20 | 19/09/2018 | 53 | 11/11/2018 | 50 | 31/12/2018 | 133 | 30/01/2019 | 28/11/2018 | 7/12/2018 | 21/12/2018 |
| 6/09/2018 | 18 | 24/09/2018 | 51 | 14/11/2018 | 49 | 2/01/2019 | 129 | 31/01/2019 | 30/11/2018 | 10/12/2018 | 24/12/2018 |
| 13/09/2018 | 15 | 28/09/2018 | 48 | 15/11/2018 | 49 | 3/01/2019 | 126 | 1/02/2019 | 2/12/2018 | 11/12/2018 | 25/12/2018 |
| 20/09/2018 | 15 | 5/10/2018 | 46 | 20/11/2018 | 46 | 5/01/2019 | 122 | 4/02/2019 | 5/12/2018 | 15/12/2018 | 29/12/2018 |
| 27/09/2018 | 16 | 13/10/2018 | 43 | 25/11/2018 | 45 | 9/01/2019 | 118 | 8/02/2019 | 9/12/2018 | 18/12/2018 | 2/01/2019 |
| 4/10/2018 | 17 | 21/10/2018 | 40 | 30/11/2018 | 43 | 12/01/2019 | 113 | 11/02/2019 | 14/12/2018 | 22/12/2018 | 6/01/2019 |
| 11/10/2018 | 13 | 24/10/2018 | 41 | 4/12/2018 | 42 | 15/01/2019 | 112 | 13/02/2019 | 16/12/2018 | 24/12/2018 | 7/01/2019 |
| 18/10/2018 | 10 | 28/10/2018 | 39 | 6/12/2018 | 43 | 18/01/2019 | 110 | 15/02/2019 | 19/12/2018 | 26/12/2018 | 9/01/2019 |

4.6.1.1 Number of Days to Wheat Full Emergence

The number of days to emergence ranged from 23 to 10 days (Figure 4.11). When sowing before 6/9/2018, the seed required more than approximately 20 days to emergence. Sowing on 20/9/2018, 27/9/2018 and 4/10/2018 showed a similar number of days (15, 16 and 17) to emergence. The later sowing dates of 11/10/2018 and 18/10/2018 only required 13 and 10 days to emergence, respectively.

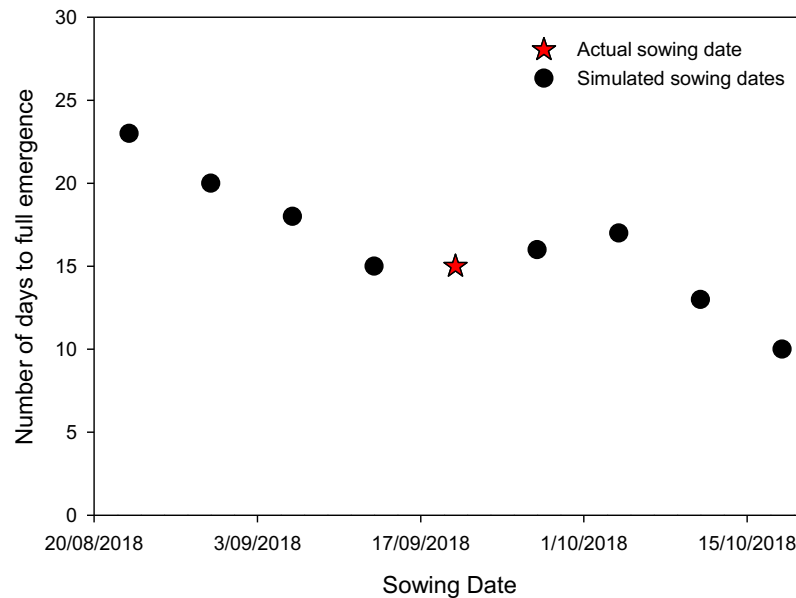


Figure 4.11 Estimated numbers of days to emergence against different simulated sowing dates for four dates before and four dates after the actual sowing date. (★) = actual sowing date (20/9/2018). (●) = simulated dates (from left to right: 23/8/2018; 30/8/2018; 6/9/2018; 13/9/2018; 27/9/2018; 4/10/2018; 11/10/2018; 18/10/2018).

4.6.1.2 Number of Days to Maximum Canopy Ground Cover

Figure 4.12 shows the longest time (53 days) to reach maximum canopy ground cover occurred when sowing on 23/8/2018 and 30/8/2018. When sowing after 27/9/2018, the time to maximum canopy ground cover was approximately 40 days (39 -41 days).

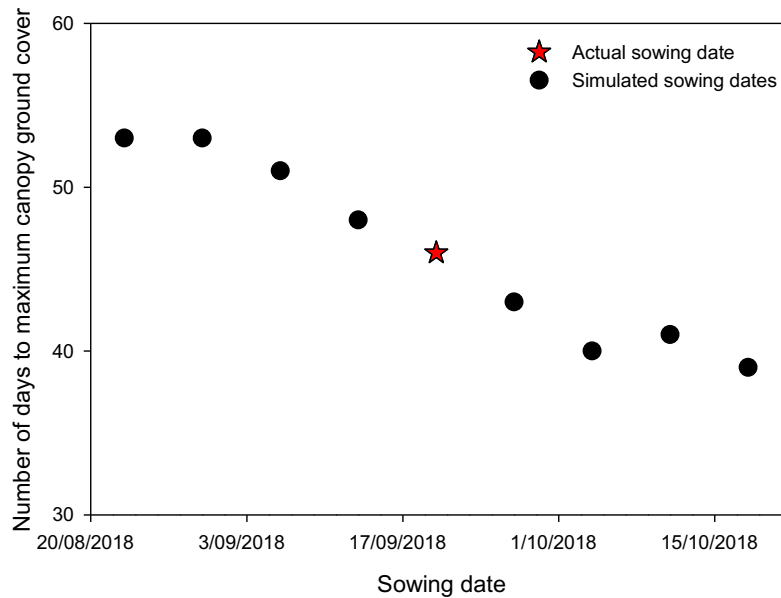


Figure 4.12 Estimated numbers of days to maximum canopy ground cover against different simulated sowing dates for four dates before and four dates after the actual sowing date. (★) = actual sowing date (20/9/2018). (●) = simulated dates (from left to right: 23/8/2018; 30/8/2018; 6/9/2018; 13/9/2018; 27/9/2018; 4/10/2018; 11/10/2018; 18/10/2018).

4.6.1.3 Number of Days from Emergence to Harvest

Figure 4.13 shows that when wheat was sown after 4/10/2018, the number of days from emergence to harvest was shorter than 110 days. Sowing earlier than 6/9/2018 had approximately 20 days more from emergence to harvest than sowing after 4/10/2018.

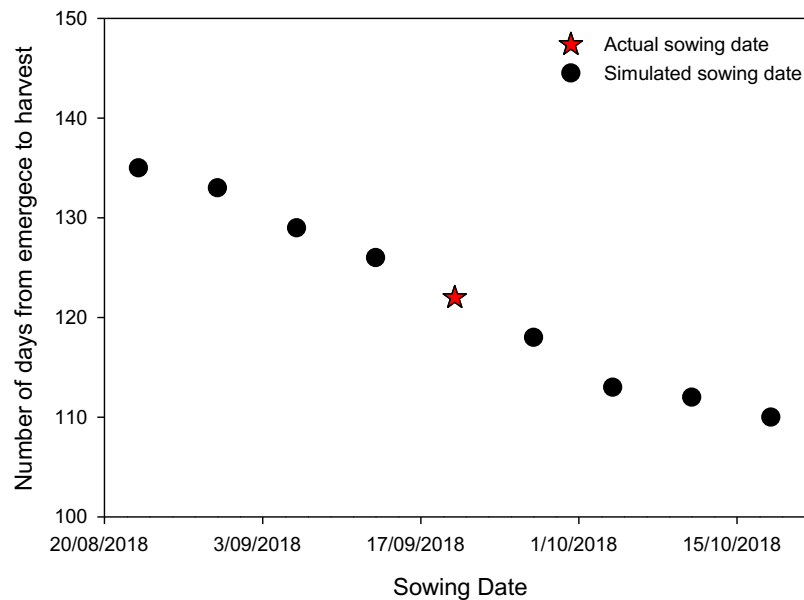


Figure 4.13 Estimated numbers of days from emergence to harvest against different simulated sowing dates for four dates before and four dates after the actual sowing date. (★) = actual sowing date (20/9/2018). (●) = simulated dates (from left to right: 23/8/2018; 30/8/2018; 6/9/2018; 13/9/2018; 27/9/2018; 4/10/2018; 11/10/2018; 18/10/2018).

4.6.1.4 Total Amount of Radiation Intercepted

Figure 4.14 shows that wheat sown earlier than 30/8/2018 had the highest total solar radiation intercepted (more than 1100 MJ/m²). When sowing later than 4/10/2018, total solar radiation intercepted was lower than 1000 MJ/m².

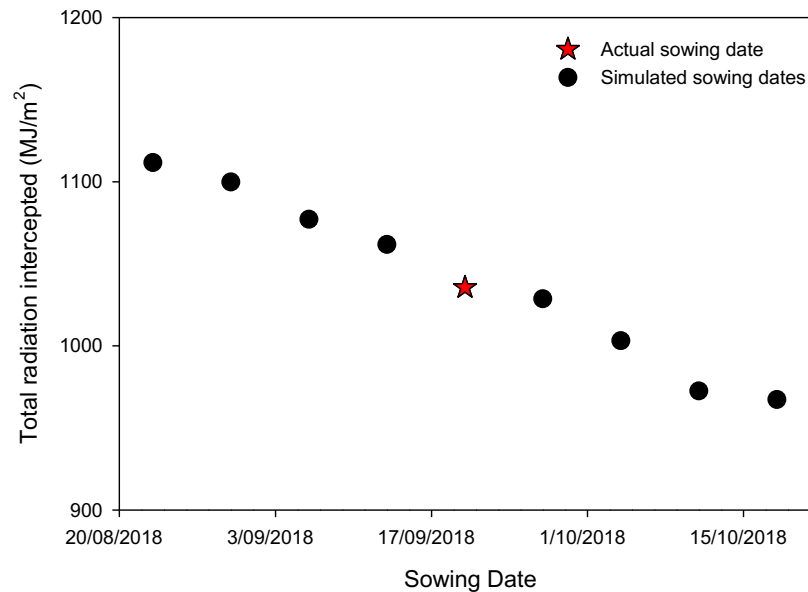


Figure 4.14 Estimated total radiation intercepted (MJ/m²) against different simulated sowing dates for four dates before and four dates after the actual sowing date. (★) = actual sowing date (20/9/2018). (●) = simulated dates (from left to right: 23/8/2018; 30/8/2018; 6/9/2018; 13/9/2018; 27/9/2018; 4/10/2018; 11/10/2018; 18/10/2018).

4.6.1.5 Wheat Available Radiation at Flag Leaf

Figure 4.15 shows that wheat sown on 23/8/2019 had the lowest available radiation at flag leaf (13 MJ/m²) and the highest radiation occurs on sowing on 11/10/2018 and 18/10/2018 (around 14 MJ/m²). There was a slight change of a 1 MJ/m² between earliest and latest sowings.

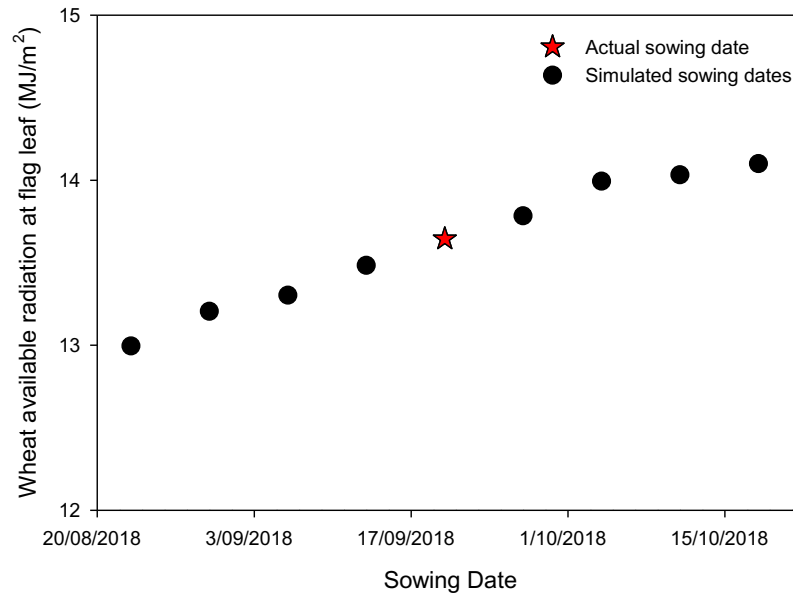


Figure 4.15 Wheat available radiation at flag leaf in an olive – wheat agroforestry system against different simulated sowing dates for four dates before and four dates after the actual sowing date. (★) = actual sowing date (20/9/2018). (●) = simulated dates (from left to right: 23/8/2018; 30/8/2018; 6/9/2018; 13/9/2018; 27/9/2018; 4/10/2018; 11/10/2018; 18/10/2018).

Chapter 5. Discussion

Agroforestry systems can provide environmental, economic and social benefits. However, these systems are still not largely studied and applied around the world compared with conventional monocultures.

Olive is a highly alternate production tree in Canterbury with a high yield in one year (the “on” year) and a low yield in the following year (the “off” year). Its production depends on the vegetative growth and development from the “off” year (Fernandez-Escobar et al., 1999; Lavee, 2007). This experiment found that olive yields were unlikely to be influenced by wheat or wheat undersown with clover intercropping which represent an opportunity for olive growers in this region.

5.1 Olive Vegetative Growth and Development

In this experiment, shoot growth of olive trees was not influenced by olive intercropping with wheat or wheat and clover. The shoot growth rate from the olive monoculture (control treatment) was not different from the intercropping treatments (Table 4.1). Maximum shoot length and the time of shoot elongation termination were also unaffected by the intercropping treatments.

Shoot elongation is affected by hormones such as auxins (Leyser, 2017). Auxin has a positive effect on gibberellin which promotes cell elongation (Taiz et al., 2015). In essence, auxin and gibberellin increase the distance between nodes, making the distance between the branch points further. Auxin synthesis is catalyzed by enzymes and the temperature affects the synthesis indirectly by influencing enzyme activity (Leyser, 2017). Moreover, the transport of auxin consumes energy which is supplied by cellular respiration. Temperature affects cellular respiration by affecting enzyme activity, which in turn affects energy supply. Therefore, air temperature can influence shoot elongation by affecting auxin synthesis and transportation (Ludwig-Müller, 2011). Air temperature was unchanged across all treatments in this experiment.

In addition, incident light and leaf chlorophyll concentration affect photosynthesis, influencing the production of carbohydrate and oxygen which are important for respiration (Taiz et al., 2015). Therefore, incident light and leaf chlorophyll concentration can influence shoot

elongation by affecting photosynthesis. In this experiment, the chlorophyll concentration of the olive leaves was unaffected by intercropping treatment (Table 4.4).

Furthermore, leaf development was uninfluenced by the intercropping treatments (Table 4.2). The rate of leaf appearance and the time of leaf growth termination were the same across treatments (Table 4.2). Auxin promotes leaf differentiation (Scarpella et al., 2010) and temperature can affect auxin by influencing the activity of related enzymes, thus affecting the appearance of leaves. In this experiment, intercropping treatments had no influence on air temperature.

Moreover, olive leaf dry matter and leaf fresh matter from the fallow control treatment were not different from the intercropping treatments (Table 4.5). Auxin and cytokinin can both promote cell division and growth (Leyser, 2017; Ludwig-Müller, 2011) and temperature affects their activity. Light and chlorophyll concentration affect leaf fresh matter and dry matter by influencing the rate at which photosynthesis accumulates carbohydrate (Taiz et al., 2015). Air temperature and the intercepted radiation from olive trees were both unchanged across treatments and chlorophyll concentration was unaffected by intercropping treatments (Table 4.4).

Mineral nutrients also influence the rate of growth and development of the leaves (Boussadia et al., 2010). Nitrogen and phosphorus can stimulate leaf area enlargement and potassium can not only promote leaf area, but also delay leaf senescence. In this experiment, intercropping had no influence on leaf nutrient content (Table 4.6).

This study contrasts with the finding of Razouk et al. (2016) who found that vegetative growth of olive tree differed when intercropped with wheat. They showed that shoot length was reduced by 40% compared with olives grown in monoculture. The authors attributed this reduction to soil moisture and nutrient competition between wheat and olives. However, they provided no data to support this. In this experiment, soil moisture and olive leaf nutrient content were unaffected across treatments (Figure 4.2; Table 4.6). Shoot length measurements were not clear in the report of Razouk et al. (2016) and their shoot initial length was an uncertain factor, which could have influenced their results.

Olive vegetative growth and development in this study were not influenced by clover. This contrasts with the findings of Razouk et al. (2016) who found that an intercrop of faba beans improved olive shoot elongation by 14%-30% compared with olive monoculture. A similar finding was reported by Li et al. (1993) who found that the growth rate of poplar trees intercropped with soy bean was twice the rate of trees intercropped with wheat. Nitrogen-fixing species have the ability to capture nitrogen from the atmosphere for growth and development. Nitrogen transfer between plants intercropped with legumes has also been reported (Ofori & Stern, 1987). Transfer of nitrogen from legume to non-legume plants is related to the amount of nitrogen fixed (Ofori & Stern, 1987). The more nitrogen a legume captures from the atmosphere, the more it can transfer to the other plants in a legume based agroforestry. Therefore, the use of legumes can increase the content of nitrogen in the soil and mitigate the competition of nutrients in the soil (Ito et al., 1997). The lack of any influence for the clover crop on olive growth and development in this experiment, might be because of the light competition between wheat and clover which reduced clover to provide nitrogen. According to Willey et al. (1983), when maize is intercropped with a legume, the maize reduces the available light to the legume by approximately 33%. Similarly, in this experiment, the light available for clovers was likely to have been reduced by the shading by wheat causing a decrease in chlorophyll content and a decrease in photosynthesis rate, reducing the growth and development of clovers. In the experiment of Wahua and Miller (1978), legume intercropped with a tall sorghum cultivar reduced the nitrogen fixation rate of the legume by 99% compared to a short sorghum. Therefore, it is possible that in this experiment the nitrogen fixation rate of clover was reduced by the wheat crop.

From the results of this work, it seems that this type of agroforestry system could benefit from growing wheat and clover crops in separate rows. This would reduce the amount of shading by the wheat crop and possibly improve the clover growth and nitrogen fixation rates.

This experiment only studied the effect of white clover on the vegetative growth of olive trees in a single season (a "off" year) and residual nitrogen from clover roots which can benefit the trees in the following year (Nair et al., 1979; Ofori & Stern, 1987). Whether this benefit will occur on olive trees would require longer investigation.

Olive intercrops with wheat or wheat and clover had no influence on olive canopy growth. Using the equation 1 ($Y = R_0 \cdot R/R_0 \cdot RUE \cdot HI$) described in section 2.3.1.2, radiation use efficiency (RUE) and harvest index (HI) were unchanged. Daily incident radiation (R_0) was unchanged for olive trees. Radiation intercepted by the canopy (R/R_0) was influenced by canopy which was unaffected by intercropping treatment. This suggests that intercropping is unlikely to reduce olive yield, representing an opportunity for growers in these regions.

5.2 Cultivars Differences

This study included three olive tree cultivars Barnea, Frantoio and Leccino. Frantoio and Leccino are reportedly high yielding cultivars, while Barnea is a considered low yielding cultivar in New Zealand (Waimea Nurseries, 2014). This experiment suggested that the different yield performances are likely caused by their different vegetative growth and development patterns.

These three cultivars had similar rates of shoot growth and shoot elongation duration (Table 4.1). The results are aligned with the findings of Perica et al. (2008). In their experiment, Frantoio and Leccino also produced similar shoot length under the same conditions.

Crude protein content of leaves for the three cultivars was similar. However, some mineral contents varied (Table 4.6). The three most important mineral nutrients for olive yield are nitrogen (N), phosphorus (P) and potassium (K) (Fernandez-Escobar et al., 1999).

There were no significant differences in N contents among cultivars and Barnea had the lowest content (Table 4.6). Nitrogen in leaves can affect olive yield by influencing fruit set (Erel et al., 2013). Yield losses can be expected for N contents higher than 1.8% or lower than 1.35% (Erel et al., 2013). This would suggest that a lower fruit setting rate should be expected for Barnea compared with the other two cultivars on the following 'on' year. It is likely that a lower nitrogen content in Barnea leaves may reflect in its low yield ability.

Differences in P contents were found among cultivars ($P < 0.01$) in this experiment (Table 4.6). Leccino leaves had higher P contents than Frantoio and Barnea. In addition to affecting fruit setting, P influences the total number of flowerings and final number of perfect flowers (having both stamens and pistils) (Erel et al., 2013; Erel et al., 2016; Jiménez-Moreno & Fernández-

Escobar, 2017). The results found in this study suggest that Leccino could have a higher yield compared with Frantoio and Barena in the next year.

In this experiment, significant different K contents were found in Frantoio, Barnea and Leccino (Table 4.6). The amount of K in Barnea leaves was approximately half that found in Frantoio and Leccino. Instead of influencing flower and fruit set, K increases yield by increasing the pulp size in the fruit (olive oil is mainly concentrated in the pulp) (Inglese et al., 2002; Rosati et al., 2015). Moreover, Mimoun et al. (2004) reported that K also can improve olive quality by increasing fruit size and pulp/pit ratio. Therefore, it is likely that olive oil yield of Barnea in the next “on” year will be lower.

From this study, it is likely that the different yield abilities of the three cultivars is influenced by leaf nutrient accumulation. Barnea had lower N, P and K contents than Frantoio and Leccino in the “off” year of this work. It is possible that this could lead to a poorer yield performance in the following “on” year. By contrast, the P content of Leccino and K content of Frantoio leaves were higher, which provides a potential higher yield for next season.

5.3 Animal Fodder

This experiment found that olive leaves had great potential for use as animal fodder with more than 13 nutrients found in their leaves from three cultivars (Table 4.6). Olive leaves also contain other valuable substances which were not measured in this experiment, including antioxidants (phenolic compounds) (Govaris et al., 2010), fibres and amino acids (García et al., 2003). These leaf attributes suggest the potential of olive leaf as animal fodder. Similar findings has been extensively reported in the literature (García et al., 2003; Molina-Alcaide & Yáñez-Ruiz, 2008).

As discussed in section 2.2.2, olive leaves provide benefits to livestock production by improving milk quality (Abbeddou et al., 2011; Zilio et al., 2015) and improving the quality of poultry and ruminant meat (Govaris et al., 2010; Morales & Ungerfeld, 2015). Based on the finding of this study and reports of others, olive leaves are useful in the diets of livestock.

During this experiment, pruning of the olive trees caused many leaves to fall. In many countries, these leaves are burned or thrown away (Xie et al., 2013). Burning causes environmental pollution and the removal of leaves wastes nutrients, especially as the nutrient content of leaves during an “off” year are higher (section 2.4.1).

Baed on these results, an environmentally responsible, profitable way to manage olive leaves can be suggested: selling them as animal fodder. This would avoid pollution and recycle nutrients through animal faeces. The higher nutrient content of leaves during an “off” year, could improve livestock diets and result in higher quality products. Moreover, this would provide additional economic benefits to the owner of the olive grove especially in an “off” year. Revenue will inevitably be reduced during this year but selling tree fodder could provide an additional income source.

5.4 Final Yields of Wheat

Legume intercropping can improve wheat grain quality due to their nitrogen-fixing ability (Thorsted et al., 2006). However, this experiment found that wheat undersown with clover had no influence on yield and wheat grain quality (Table 4.10; Table 4.11).

As discussed in section 2.3.1.2, crop yield generally relies on four components (daily incident radiation (R_0), radiation intercepted by the canopy (R/R_0), radiation use efficiency (RUE), and harvest index (HI)). Compared with milling wheat sown alone in this experiment, the wheat canopy ground cover was not influenced by the clover undersowing.

Wheat emergence was not affected by the clover undersown (Table 4.8). Emergence is mostly influenced by soil temperature and moisture (Khah et al., 1986). These factors were unchanged in the clover intercropping. Furthermore, the dynamic of the milling wheat canopy expansion (time to maximum green canopy ground cover and its duration at maximum cover) were not different between treatments (Table 4.9). According to Moeller et al. (2014), tillering is one of the most important factors influencing crop canopy ground cover. Wheat tillering is mainly affected by temperature and soil moisture (Chaturvedi et al., 1981). Air temperature lower than 4 °C or higher than 33 °C (Krishnan et al., 2011) and limited water availability (Chaturvedi et al., 1981) are unfavorable for tillering. In this experiment, wheats were not under temperature and

water stress in both treatments (Figure 3.3; Figure 4.1) Although the number of tillers was not measured in this work, temperature was recorded at 10 to 13 °C (Figure 4.1) and soil moisture (Figure 4.2) was similar for the two wheat treatments during the crop canopy growing phase. In addition, the wheat nitrogen and phosphorus contents, often related to tillering patterns in wheat (Liang & Kang, 1977; Zhang et al., 2018), were similar across treatments as measured in the wheat grain (Table 4.11).

Quality of bread wheat is determined by the protein content of the grain (Hay & Porter, 2006). In this experiment, grain quality was not improved by clover intercropping (Table 4.11). According to Thorsted et al. (2006), clover intercropping can improve wheat grain quality due to its nitrogen-fixing ability. It is possible that the lack of any wheat grain quality improvement from the clover treatment is related to the excess shading of the clover species in those plots. This could have led to lower rates of clover photosynthesis (Wahua & Miller, 1978) and growth rate (Zhang et al., 2008). It follows that if the nitrogen fixing ability of a legume species is directly associated with the plant growth rate, it is unlikely that the clover influenced the soil nitrogen status available for the wheat crop (Zhang et al., 2008).

The olive trees imposed a reduction in the total available light for the wheat crop (Figure 4.3). The photosynthesis saturation point (beyond which any increment in the radiation levels does not reflect in an increase in the crop leaf photosynthetic rate) of wheat crops is 20 MJ/m² (Acevedo et al., 2002). In this study, the maximum mean available radiation for wheat intercropped with olive trees was about 15 MJ/m² (Figure 4.3). Therefore, it is plausible to assume that this reduction of incident radiation (R_o) reduced the potential wheat yield by approximately 25%.

Wider olive row spacings and canopy pruning can effectively improve the total available radiation in agroforestry systems (Everson et al., 2004; Gao et al., 2013). However, wider spacings would compromise the total yield capacity of olive trees on an area basis. Moreover, pruning is likely to affect the yield of trees in the following season. Optimum pruning regimes along with olive row orientation could be investigated for better PAR availability to the intercropped species. These management practices are likely to improve the yield potential of wheat crops in olive

groves in the Canterbury region, which suggests that the price paid after harvest of each intercropped species and the cost generated by the different management strategies, would dictate the most appropriate agronomic practices.

The basic physiological principles of agroforestry systems suggest that the species composition design and management practices should be determined based on the species phenology and physiology. The understanding of the phenology of the different species intercropped often presents opportunities and constraints to the yield quality of all the harvestable components in the system. The understanding of the species phenology and their potential complementarity in time and space is a major discussion area in the agroforestry literature (Mao & Zeng, 2009).

5.5 Sensitivity Analysis of Species Phenology

Mao and Zeng (2009) reported that understanding the phenological characteristics of species is important in creating an agroforestry system. In order to maximize the production of this system, the use of resources among species should follow a pattern of complementary (section 2.1.1). Olive and wheat agroforestry systems have been widely used in European countries but there is no reporting of these systems in New Zealand (AGFORWARD, 2014). Following the results found in this work, a sensitivity analysis was performed to investigate how different spring milling wheat sowing dates could be tailored to improve the species phenological complementary.

The sensitivity analysis showed that for the wheat sowings prior to 6/9/2018, the seeds required more than about 20 days to reach full emergence (Figure 4.11). Kaiser et al. (1989) reported that slower emergence favored diseases and caused seeding rot, reducing plant populations. Therefore, this suggests that with these earlier sowing dates, milling wheat crop establishment and yields could decrease.

This sensitivity analysis further showed that early sowings of wheat in Canterbury, but not before 6/9/2018, are likely to improve yield. Total radiation interception (Hay & Porter, 2006) and available radiation at flag leaf (Birsin, 2005) are two important factors that determine wheat yield. The analysis presented here showed that sowing wheat up to two weeks earlier than the

20/9/2018 increased the crop growing season by about 10 days (Figure 4.13) and improved total crop radiation interception by about 10% (Figure 4.14) although the time to maximum canopy ground cover was later (Figure 4.12), compared with sowing on 20/9/2018 in this region. However, it is important to consider that a longer growing season increases the possibility of wheat being affected by pests and diseases, especially in spring (Jiang et al., 2011). There was a slight change (1 MJ/m^2) in available radiation at flag leaf for all sowing dates in this work (Figure 4.15). However, this small change is unlikely to influence yield.

Although the total radiation interception by the crop was reduced with later sowings, an opportunity to improve grain quality was found. An increase in temperature from 20 to 30 °C during wheat anthesis (Hay & Porter, 2006) and crop canopy shading after flowering (during grain filling) can improve grain protein content (Qiao et al., 2019). For all sowing dates in the model, wheat anthesis occurred during December (Table 4.12) when the average temperature was lower than 20 °C (Figure 4.1). However, when sowing date was delayed, the wheat grain fill (GS 71) period was also delayed and this coincided with higher levels of shading from the olive trees. This could represent an opportunity to improve wheat grain protein content (a milling wheat quality attribute) with later sowing dates. However, any quality improvement from later sowing would possibly be accompanied by the cost of a wheat grain yield decrease. This means that the wheat sowing date in those systems would be determined by the price paid for the higher protein of the wheat grain. This could be tested in the future with additional field experiments in an olive and wheat agroforestry system.

Moreover, the later sowings can lead to an overlapping of physiological stages of the two species, when nutrient demand for crop grain filling and olive reproductive development (such as flowering) coincide. This experiment found that olive vegetative growth and development terminated in January (Figure 4.4; Figure 4.5). Reproductive development of olive trees occurred in January following the termination of vegetative growth and development and is a phase with high demands for nitrogen, phosphorus and potassium (Erel et al., 2013; Inglese et al., 2002). Moreover, late sowings (after 4/10/2018) of wheat delayed the grain filling period (GS 71), which also occurred in January (Table 4.12), when there is also a higher demand for nutrients such as nitrogen (Roberts & Heady, 1982). This overlap could have adverse effects on fruit development

of olive trees and grain filling of wheat in agroforestry systems where soil nutrient availability is limited.

5.6 Conclusion

Based on the findings of this study, the following conclusions can be drawn;

- In these intercropping systems, olive tree vegetative growth and development was unaffected by wheat or wheat undersown with clover.
- There was no difference in shoot elongation and leaf appearance among the tree cultivars in this study, but Barnea had the lowest N, P and K of all olive cultivars in the “off” year which could lead to a lower olive yield for this cultivar in the following “on” year.
- Olive leaves were shown to contain more than 13 nutrients and these leaves could be used as animal fodder. This could provide an additional income source for growers during an “off” year.
- Olive and wheat intercropping decreased the available radiation for wheat and this lowered the potential wheat yield by 25%. Tree pruning could be used to increase available radiation for the wheat and increase the wheat yield. Also, there is a potential for the wheat grain quality to be improved through shading by the olive trees.
- In the Canterbury region, in an olive and wheat intercropping system, sowing the wheat before the 6 of September could result in a longer emergence time which could lead to seeding rot. Early sowings of wheat but not before 6 of September, are likely to improve yield. Late sowings (after the 4 of October) are likely to improve grain quality but enhance the nutrient competition between the wheat and the olive trees.

Reference

- Abbeddou, S., Rischkowsky, B., Richter, E. K., Hess, H. D., & Kreuzer, M. (2011). Modification of milk fatty acid composition by feeding forages and agro-industrial byproducts from dry areas to Awassi sheep. *Journal of Dairy Science*, 94(9), 4657-4668.
- Acevedo, E., Silva, P., & Silva, H. (2002). Wheat growth and physiology. *Bread Wheat, Improvement and Production*, 30.
- AGFORWARD. (2014). *Intercropping of olive groves in Greece*. Retrieved from <https://www.agforward.eu/index.php/en/intercropping-of-olive-groves-in-greece.html>
- Aguilera, F., & Ruiz Valenzuela, L. (2013). Time trend in the viability of pollen grains in the 'Picual' olive (*Olea europaea* L.) cultivar. *Palynology*, 37(1), 28-34.
- Aguilera, M. P., Beltrán, G., Ortega, D., Fernández, A., Jiménez, A., & Uceda, M. (2005). Characterisation of virgin olive oil of Italian olive cultivars: Frantoio' and Leccino', grown in Andalusia. *Food chemistry*, 89(3), 387-391.
- Allen, E. J., & Scott, R. K. (1980). An analysis of growth of the potato crop. *Journal of Agricultural Science*, 94, 583-606.
- Arquero, O., Barranco, D., & Benlloch, M. (2006). Potassium starvation increases stomatal conductance in olive trees. *HortScience*, 41(2), 433-436.
- Atangana, A., Khasa, D., Chang, S., & Degrande, A. (2014). Agroforestry Modeling. In *Tropical Agroforestry* (pp. 367-373). Dordrecht: Springer.
- Autstin, P. T., Hall, A. J., Gandar, P. W., Warrington, I. J., Fulton, T. A., & Hallingam, E. A. (1999). A compartment model of the effect of early-season temperatures on potential size and growth of 'Delicious' apple fruits. *Annals of Botany*, 83, 129-143.
- Baker, C. K., & Gallagher, J. N. (1983). The development of winter wheat in the field. 2. The control of primordium initiation rate by temperature and photoperiod. *The Journal of Agricultural Science*, 101(2), 337-344.
- Barro, R. S., Saibro, J. C. D., Medeiros, R. B. D., Silva, J. L. S. D., & Varella, A. C. (2009). Rendimento de forragem e valor nutritivo de gramíneas anuais de estação fria submetidas a sombreamento por *Pinus elliottii* e ao sol pleno. *Revista Brasileira de Zootecnia*, 37(10), 1721-1727.
- Bennell, M. R., Cleugh, H. A., Leys, J. F., & Hein, D. (2007a). The effect of hot dry wind on the pod set of faba bean (*Vicia faba*) cv. Fiord: A preliminary wind tunnel study. *Aust. J. Exp. Agric.*, 47(12), 1468-1475.
- Bennell, M. R., Leys, J. F., & Cleugh, H. A. (2007b). Sandblasting damage of narrow-leaf lupin (*Lupinus angustifolius* L.): A field wind tunnel simulation. *Aust. J. Soil Res.*, 45(2), 119-128.
- Bertomeu, M. (2012). Growth and yield of maize and timber trees in smallholder agroforestry systems in Claveria, northern Mindanao, Philippines. *Agroforestry systems*, 84(1), 73-87.
- Birsin, M. A. (2005). Effects of removal of some photosynthetic structures on some yield components in wheat. *Tarim Bilimleri Dergisi*, 11(4), 364-367.
- Blanford, H. R. (1958). Highlights of one hundred years of forestry in Burma. *Empire Forestry Review*, 37(1 (91), 33-42.(1), 33-42.
- Bonhomme, R. (2000). Bases and limits to using 'degree.day' units. *European Journal of Agronomy Journal*, 13, 1-10.
- Borthwick, H. A., Hendricks, S. B., Toole, E. H., & Toole, V. K. (1954). Action of light on lettuce-seed germination. *Botanical Gazette*, 115(3), 205-225.
- Bouhafa, K., Moughli, L., Daoui, K., Douaik, A., & Taarabt, Y. (2015). Soil properties at different distances of intercropping in three olive orchards in Morocco. *International Journal of Plant & Soil Science*, 7, 238-245.

- Bouillet, J. P., Laclau, J. P., Gonçalves, J. L. M., Moreira, M. Z., Trivelin, P. C. O., Jourdan, C., . . . Galiana, A. (2008). Mixed-species plantations of *Acacia mangium* and *Eucalyptus grandis* in Brazil: 2: Nitrogen accumulation in the stands and biological N₂ fixation. *Forest Ecology and Management*, 255(12), 3918-3930.
- Boussadia, O., Steppe, K., Zgallai, H., El Hadj, S. B., Braham, M., Lemeur, R., & Van Labeke, M. C. (2010). Effects of nitrogen deficiency on leaf photosynthesis, carbohydrate status and biomass production in two olive cultivars 'Meski' and 'Koroneiki'. *Scientia Horticulturae*, 123(3), 336-342.
- Breton, C., & Bervillé, A. (2013). From the olive flower to the drupe: flower types, pollination, self and inter-compatibility and fruit set. *Horticultural reviews*, 31, 155-229.
- Brown, P. H. (1994). Seasonal variations in fig (*Ficus carica* L.) leaf nutrient concentrations. *HortScience*, 29(8), 871-873.
- Buck, L. E., Lassoie, J. P., & Fernandes, E. C. (1998). *Agroforestry in sustainable agricultural systems*: CRC Press.
- Burgess, P. J., Graves, A., García de Jalón, S., Palma, J. H. N., Dupraz, C., & van Noordwijk, M. (2019). Modelling agroforestry systems. In M.-L. M.R. & R. Prabhu (Eds.), *Agroforestry for Sustainable Agriculture* (pp. 209-238). Cambridge: Burleigh Dodds Science Publishing.
- Cai, Q. S., & Wu, Z. S. (1993). The relationship between dry matter accumulation and grain weight in wheat grain growth stages. *Journal of Nanjing Agricultural University*, 16(1), 27-32.
- Caradus, J. R., Woodfield, D. R., & Stewart, A. V. (1996). Overview and vision for white clover. *Agronomy Society of New Zealand*(1-6).
- Charlton, J. F. L., Douglas, G. B., Wills, B. J., & Prebble, J. E. (2003). Farmer experience with tree fodder. Using trees on farms. *Grassland research and practice series*, 10, 7-15.
- Chaturvedi, G. S., Aggarwal, P. K., Singh, A. K., Joshi, M. G., & Sinha, S. K. (1981). Effect of irrigation on tillering in wheat, triticale and barley in a water-limited environment. *Irrigation Science*, 2(4), 225-235.
- Cheema, U. B., Sultan, J. I., Javaid, A., Akhtar, P., & Shahid, M. (2011). Chemical composition, mineral profile and in situ digestion kinetics of fodder leaves of four native trees. *Pak. J. Bot*, 43(1), 397-404.
- Chinese Flora. (1997). 橄欖. Retrieved from <http://frps.iplant.cn/frps?id=%e6%a9%84%e6%a6%84>
- Chirko, C. P., Gold, M. A., Nguyen, P. V., & Jiang, J. P. (1996). Influence of direction and distance from trees on wheat yield and photosynthetic photon flux density (Qp) in a Paulownia and wheat intercropping system. *Forest Ecol Manag*, 83, 171-180.
- Coelho, C. M. M., & Benedito, V. A. (2008). Seed development and reserve compound accumulation in common bean (*Phaseolus vulgaris* L.). *Seed Sci. Biotechnol*, 2(2), 42-52.
- Danso, S. K. A., Bowen, G. D., & Sanginga, N. (1992). Biological nitrogen fixation in trees in agro-ecosystems. In *Biological Nitrogen Fixation for Sustainable Agriculture* (Vol. 177-196). Dordrecht: Springer.
- Daoui, K., & Fatemi, Z. E. A. (2014). Agroforestry systems in Morocco: the case of olive tree and annual crops association in Sais region. In *Science, Policy and Politics of Modern Agricultural System* (pp. 281-289). Dordrecht: Springer.
- de Jalón, S. G., Graves, A., Palma, J. H., Williams, A., Upson, M., & Burgess, P. J. (2018). , 92(4), 1059-1073. (2018). Modelling and valuing the environmental impacts of arable, forestry and agroforestry systems: a case study. *Agroforestry systems*, 92(4), 1059-1073.
- De Reffye, P., Houllier, F., Blaise, F., Barthélémy, D., Dauzat, J., & Auclair, D. (1995). A model simulating above-and below-ground tree architecture with agroforestry applications. *Agroforestry systems*, 30, 1-2.
- Devendra, C. (1992). Nutritional potential of fodder trees and shrubs as protein sources in ruminant nutrition. *Legume trees and other fodder trees as protein sources for livestock*, 100, 95-113.

- Dixon, R. K. (1995). Agroforestry systems: sources of sinks of greenhouse gases? *Agroforestry systems*, 31(2), 99-116.
- Eichhorn, M. P., Paris, P., Herzog, F., Incoll, L. D., Liagre, F., Mantzanas, K., . . . Dupraz, C. (2006). Silvoarable systems in Europe—past, present and future prospects. *Agroforestry systems*, 67(1), 29-50.
- Erel, R., Yermiyahu, U., Van Opstal, J., Ben-Gal, A., Schwartz, A., & Dag, A. (2013). The importance of olive (*Olea europaea* L.) tree nutritional status on its productivity. *Scientia Horticulturae*, 159, 8-18.
- Erel, R., Yermiyahu, U., Yasuor, H., Chamus, D. C., Schwartz, A., Ben-Gal, A., & Dag, A. (2016). Phosphorous nutritional level, carbohydrate reserves and flower quality in olives. *PloS one*, 11(12).
- Evans, L. T., & Rawson, H. M. (1970). Photosynthesis and respiration by the flag leaf and components of the ear during grain development in wheat. *Australian journal of biological sciences*, 23(2), 245-254.
- Everson, T. M., Everson, C., & Van Niekirk, W. (2004). Agroforestry in rural farming systems: a case study from the Drakensberg mountains in KwaZulu-Natal. In E. H. Lawes MJ, Shackelton CM, Geach BGS (Ed.), *Indigenous forests and woodlands in South Africa* (pp. 650-658): University of KwaZulu-Natal Press, Pietermaritzburg.
- Fanish, S. A., & Priya, R. S. (2013). Review on benefits of agroforestry system. *International Journal of Education and Research*, 1(1), 1-12.
- Fernandez-Escobar, R., Moreno, R., & Garcia-Creus, M. (1999). Seasonal changes of mineral nutrients in olive leaves during the alternate-bearing cycle. *Scientia Horticulturae*, 82(1-2), 25-45.
- Flood, R. G., & Halloran, G. M. (1986). Genetics and physiology of vernalization response in wheat. *Advances in agronomy*, 39, 87-1235.
- Food and Agriculture Organization. (2012). *Crops*. Retrieved from <http://www.fao.org/faostat/en/#data/QC>
- Food and Agriculture Organization of the United States. (2010). *The State of Food Insecurity in the World 2010: Addressing food insecurity in protracted crises*. Rome, Italy. Retrieved from <http://www.fao.org/3/i1683e/i1683e00.htm>
- Forcella, F., Arnold, R. L. B., Sanchez, R., & Ghera, C. M. (2000). Modeling seedling emergence. *Field Crops Research*, 67(2), 123-139.
- Forest New Zealand. (2018). *The one billion trees programme our future, our billion trees*. Retrieved from <https://www.mpi.govt.nz/dmsdocument/31860/direct>
- Fujita, K., Ofosu-Budu, K. G., & Ogata, S. (1992). Biological nitrogen fixation in mixed legume-cereal cropping systems. *Plant and soil* 141(1-2), 155-175.
- Gamon, J. A., Field, C. B., Goulden, M. L., Griffin, K. L., Hartley, A. E., Joel, G., . . . Valentini, R. (1995). Relationships between NDVI, canopy structure, and photosynthesis in three Californian vegetation types. *Ecological Applications*, 5(1), 28-41.
- Gao, H. C. (2012). The effect of temperature on the growth and development of vegetables. *Gilin Vegetables*, 3, 22.
- Gao, L., Xu, H., Bi, H., Xi, W., Bao, B., Wang, X., . . . Chang, Y. (2013). Intercropping competition between apple trees and crops in agroforestry systems on the Loess Plateau of China. *PLoS One* 8(7), e70739.
- García, A. M., Moumen, A., Ruiz, D. Y., & Alcaide, E. M. (2003). Chemical composition and nutrients availability for goats and sheep of two-stage olive cake and olive leaves. *Animal Feed Science and Technology*, 107(1-4), 61-74.
- Gold, A., M. . (2017). *Agroforestry*. Retrieved from <https://www.britannica.com/science/agroforestry#ref331890>

- Govaris, A., Botsoglou, E., Moulas, A., & Botsoglou, N. (2010). Effect of dietary olive leaves and rosemary on microbial growth and lipid oxidation of turkey breast during refrigerated storage. *South African Journal of Animal Science*, 40(2).
- Hay, R. K. M., & Porter, J. R. (2006). *The physiology of crop yield*. Oxford, UK: Blackwell Publishing.
- Heraut-Bron, V., Robin, C., Varlet-Grancher, C., Afif, D., & Guckert, A. (2000). Light quality (red: far-red ratio): does it affect photosynthetic activity, net CO₂ assimilation, and morphology of young white clover leaves? *Canadian Journal of Botany*, 77(10), 1425-1431.
- Hopkins, W. G. (1999). *Introduction to plant physiology* (No. Ed. 2): John Wiley and Sons.
- Huang, Z. L. (2005). *Dictionary of earth science*: Geological Publishing.
- Hussain, J., Khaliq, T., Ahmad, A., & Akhtar, J. (2018). Performance of four crop model for simulations of wheat phenology, leaf growth, biomass and yield across planting dates. *PloS one*(13), 6.
- Inglese, P., Gullo, G., & Pace, L. S. (2002). Fruit growth and olive oil quality in relation to foliar nutrition and time of application. *Acta Horticulturae*(586), 507-509.
- Inskeep, W. P., & Bloom, P. R. (1985). Extinction coefficients of chlorophyll a and b in N, N-dimethylformamide and 80% acetone. *Plant physiology*, 77(2), 483-485.
- Ito, Y., Kaku, H., & Shibuya, N. (1997). Identification of a high - affinity binding protein for N - acetylchitoooligosaccharide elicitor in the plasma membrane of suspension - cultured rice cells by affinity labeling. *The Plant Journal*, 12(2), 347-356.
- Ivory, D. A., & Siregar, M. E. (1984). *Forage research in Indonesia: Past and present*. : Asian Pasture . FFTC Book Series.
- Jamieson, P. D., Martin, R. J., & Francis, G. S. (1995). Drought influences on grain yield of barley, wheat, and maize. *New Zealand Journal of Crop and Horticultural Science*, 23, 55-66.
- Jiang, X., Yao, S., J., & Ren, S., F. (2011). Analysis of common problems during wheat growth and countermeasures. *China agriculture technology extention*, 27(5), 20-22.
- Jiménez-Moreno, M. J., & Fernández-Escobar, R. (2017). Influence of nutritional status of phosphorus on flowering in the olive (*Olea europaea* L.). *Scientia Horticulturae*, 223, 1-4.
- Jones, H. G., Archer, N., Rotenberg, E., & Casa, R. (2003). Radiation measurement for plant ecophysiology. *Journal of Experimental Botany*, 54(384), 879-889.
- Jose, S. (2009). Agroforestry for ecosystem services and environmental benefits: an overview. *Agroforestry systems*, 76(1), 1-10.
- Kaiser, W. J., Hannan, R. M., & Weller, D. M. (1989). Biological control of seed rot and preemergence damping-off of chickpea with fluorescent pseudomonads. *Soil biology and biochemistry*, 21(2), 269-273.
- Kang, B. T., & Wilson, G. F. (1987). The development of alley cropping as a promising agroforestry technology. *Agroforestry: a decade of development*, 227-243.
- Kemp, P. D., Barry, T. N., & Douglas, G. B. (2003). Edible forage yield and nutritive value of poplar and willow. In *Proceedings of MAF Sustainable Farming Fund Workshop, Grassland Research and Practice Series*, 10, 53-63.
- Khah, E. M., Ellis, R. H., & Roberts, E. H. (1986). Effects of laboratory germination, soil temperature and moisture content on the emergence of spring wheat. *The Journal of Agricultural Science*, 107(2), 431-438.
- Kirby, K. R., & Potvin, C. (2007). Variation in carbon storage among tree species: implications for the management of a small-scale carbon sink project. *Forest Ecology and Management*, 246(2), 208-221.
- Kirchner, R., Soares, A. B., Sartor, L. R., Adami, P. F., Migliorini, F., & Fonesca, L. (2010). Desempenho de forrageiras hibernais sob distintos níveis de luminosidade. *Revista Brasileira de Zootecnia*, 39(11), 2371-2379.

- Koko, L., Snoeck, K., Lekadou, D., & Assiri, T. (2013). Cacao-fruit tree intercropping effects on cocoa yield, plant vigour and light interception in Côte d'Ivoire. *Agroforestry Systems*, 87(5), 1043-1052.
- Krishnan, P., Ramakrishnan, B., Reddy, K. R., & Reddy, V. R. (2011). High-temperature effects on rice growth, yield, and grain quality. In *Advances in agronomy* (Vol. 111, pp. 87-206): Academic Press.
- Lamanda, N., Dauzat, J., Jourdan, C., Martin, P., & Malézieux, E. (2008). Using 3D architectural models to assess light availability and root bulkiness in coconut agroforestry systems. *Agroforestry Systems*, 72(1), 63-74.
- Lavee, S. (2007). Biennial bearing in olive (*Olea europaea* L.). *Annales Ser His Nat*, 17, 101-112.
- Lawson, T. L., & Kang, B. T. (1990). Yield of maize and cowpea in an alley cropping system in relation to available light. *Agricultural and Forest Meteorology*, 52(3-4), 347-357.
- Le Houérou, H. N. (1980). Chemical composition and nutritive value of browse in tropical West Africa. Browse in Africa, the current state of knowledge. . *ILCA, Addis Ababa*, 261-289.
- Leakey, R. (1996). Definition of agroforestry revisited. *Agroforestry today*, 8, 5.
- Lehmann, J., Peter, I., Steglich, C., Gebauer, G., Huwe, B., & Zech, W. (1998). Below-ground interactions in dryland agroforestry. *Forest Ecology and Management*, 111(2-3), 157-169.
- Lelle, M. A., & Gold, M. A. (1994). Agroforestry systems for temperate climates: lessons from Roman Italy. . *Forest Conserv. HIST*, 38, 118-126.
- Leyser, O. (2017). Auxin signaling. In *Plant Physiology* (pp. 765)
- Li, L. (2013). The impact and effect of temperature on the growth and development of vegetables. *Jilin Vegerable*, 8, 16-17.
- Li, W. Z., Shi, G. H., Cui, Y. C., Zhang, J. Z., & Zhu, J. H. (1993). Intercropping of poplar fast-growing and high-yield forests. *Gansu Forestry Science and Technology*(2).
- Liang, Y. L., & Kang, S. Z. (1977). Effects of limited irrigation and phosphorus nutrition on winter wheat yield and water use. *Journal of Soil and Water Conservation*, 1.
- Lin, B. B., Burgess, A. J., & Murchie, E. H. (2015). Adaptations for climate sensitive crops using agroforestry: case studies for coffee and rice. In C. Black, Wilson, J., Ong, C.K. (Ed.), *Tree–Crop Interactions: Agroforestry in a Changing Climate* (pp. 228-308): CABI.
- Livesley, S. J., Gregory, P. J., & Buresh, R. J. (2002). Competition in tree row agroforestry systems. 2. Distribution, dynamics and uptake of soil inorganic N. *Plant and Soil*, 247(2), 177-187.
- Livesley, S. J., Gregory, P. J., & Buresh, R. J. (2004). Competition in tree row agroforestry systems. 3. Soil water distribution and dynamics. *Plant and soil*, 264(1-2), 129-139.
- Lobell, D. B., & Ortiz-Monasterio, J. I. (2007). Impacts of day versus night temperatures on spring wheat yields. *Agronomy journal*, 99(2), 469-477.
- Lu, J. M., & Yu, B. Y. (1978). Characteristics of the formation of wheat crops in the Tibetan Plateau. *Chinese Agricultural Sciences*, 11(4), 25-31.
- Lu, Q., Yang, H. X., Ci, L., Zhu, Z., Wu, Y., & Jing, Y. (1997). Effect of radiation transmission on crop yield and quality. *Acta ecologica sinica (Chinese with English abstract)*, 17(1), 36-44.
- Lucas, R. J., Smith, M. C., Jarvis, P., Mills, A., & Moot, D. J. (2010). Nitrogen fixation by subterranean and white clovers in dryland cocksfoot pastures. In *Proceedings of the New Zealand Grassland Association*, 72, 141-146.
- Lucero, D. W., Grieu, P., & Guckert, A. (2000). Water deficit and plant competition effects on growth and water-use efficiency of white clover (*Trifolium repens*, L.) and ryegrass (*Lolium perenne*, L.). *Plant and Soil*, 227(1-2), 1-15.
- Ludwig-Müller, J. (2011). Auxin conjugates: their role for plant development and in the evolution of land plants. *Journal of experimental botany*, 62(6), 1757-1773.

- Mao, R., & Zeng, D., H. (2009). Research advances in plant competition in agroforestry systems. *Chinese Journal of Eco-Agriculture*, 17(2), 379-386.
- Markin, D., Duek, L., & Berdicevsky, I. (2003). In vitro antimicrobial activity of olive leaves. Antimikrobielle Wirksamkeit von Olivenblättern in vitro. *Mycoses*, 46(3-4), 132-136.
- Marsh Jr, H. V., Evans, H. J., & Matrone, G. (1963). Investigations of the role of iron in chlorophyll metabolism. II. Effect of iron deficiency on chlorophyll synthesis. *Plant Physiology*, 38(6), 638.
- Martinez-Gracia, J. F., Galstyan, A., Salla-Martret, M., Cifuentes-Esquivel, N., Gallemi, M., & Bou-Torrent, J. (2010). Regulatory components of shade avoidance syndrome. *Advances in Botanical Research*, 53, 64-116.
- Massey University. (2016). *White Clover*. Retrieved from <http://www.massey.ac.nz/massey/learning/colleges/college-of-sciences/clinics-and-services/weeds-database/white-clover.cfm>
- McCree, K. J. (1971). The action spectrum, absorptance and quantum yield of photosynthesis in crop plants. *Agricultural Meteorology*, 9, 191-216.
- McLaren, R. G., & Cameron, K. C. (1996). *Soil science: sustainable production and environmental protection*. Auckland: Oxford University Press.
- McNeely, J., & Schroth, A. (2006). Agroforestry and Biodiversity Conservation – Traditional Practices, Present Dynamics, and Lessons for the Future. *Biodiversity & Conservation*, 15(2), 549-554.
- Mialet-Serra, I., Dauzat, J., & Auclair, D. (2001). Using plant architectural models for estimation of radiation transfer in a coconut-based agroforestry system. *Agroforestry systems*, 53(2), 141-149.
- Midmore, D. J. (1984). Potato (*Solanum* spp.) in the hot tropics I. Soil temperature effects on emergence, plant development and yield. *Field Crops Research*, 8, 255-271.
- Mimoun, M. B., Loumi, O., Ghrab, M., Latiri, K., & Hellali, R. (2004). Foliar potassium application on olive tree. *IPI Regional Workshop on Potassium and Fertilization Development in West Asia and North Africa*.
- Moeller, C., Evers, J. B., & Rebetzke, G. (2014). Canopy architectural and physiological characterization of near-isogenic wheat lines differing in the tiller inhibition gene tin. *Frontiers in plant science*, 5, 617.
- Molina-Alcaide, E., & Yáñez-Ruiz, D. R. (2008). Potential use of olive by-products in ruminant feeding: A review. *Animal Feed Science and Technology*, 147(1-3), 247-263.
- Monneveux, P., Reynolds, M. P., González - Santoyo, H., Pena, R. J., Mayr, L., & Zapata, F. (2004). Relationships between grain yield, flag leaf morphology, carbon isotope discrimination and ash content in irrigated wheat. *Journal of Agronomy and Crop Science*, 190(6), 395-401.
- Monteith, J., & Unsworth, M. (2013). *Principles of environmental physics: plants, animals, and the atmosphere*: Academic Press.
- Monteith, J. L. (1977). Climate and the efficiency of crop production in Britain. *Philosophical Transactions of the Royal Society of London*, 281, 277-294.
- Monteith, J. L. (1994). Validity and utility of the correlation between intercepted radiation and biomass. *Meteorol*, 68, 213-220.
- Monteith, J. L. (2000). Agricultural meteorology: Evolution and application. *Agricultural and Forest Meteorology*, 103, 5-9.
- Monteith, J. L., Ong, C. K., & Corlett, J. E. (1991). Microclimate interactions in agroforestry systems. *Forest Ecol. Manag.*, 45, 31-44.
- Morais, H., Caramori, P. H., Ribeiro, A. M. D. A., Gomes, J. C., & Kogushi, M. S. (2006). Microclimatic characterization and productivity of coffee plants grown under shade of pigeon pea in Southern Brazil. *Pesquisa agropecuária brasileira*, 41(5), 763-770.
- Morales, R., & Ungerfeld, E. M. (2015). Use of tannins to improve fatty acids profile of meat and milk quality in ruminants: A review. *Chilean journal of agricultural research*, 75(2), 239-248.

- Muchow, R. C., & Bellamy, J. A. (1991). Climatic risk in crop production: Models and management for the semiarid tropics and subtropics. from CAB international
- Murthy, I. K., Gupta, M., Tomar, S., Munsi, M., Tiwari, R., Hegde, G. T., & Ravindranath, N. H. (2013). Carbon sequestration potential of agroforestry systems in India. *J Earth Sci Climate Change*, 4(1), 1-7.
- Nair, K., Patel, U., Singh, R., & Kaushik, M. (1979). Evaluation of legume intercropping in conservation of fertilizer nitrogen in maize culture. *The Journal of Agricultural Science*, 93(1), 189-194.
- Nair, P. K. R., Budowski, G., & Steppeler, H. A. (1987). *The development of agroforestry in Central America Agroforestry; a decade of development* (No. 30221). Nairobi (Kenia).
- Nandal, D. P. S., & Bisla, S. S. (1995). Growing oats under trees for more and better fodder. *Agroforestry Today*, 7(1), 1-12.
- Newman, S. M., Bennett, K., & Wu, Y. (1997). Performance of maize, beans and ginger as intercrops in Paulownia plantations in China. *Agroforestry Systems*, 39(1), 23-30.
- Ng, F. (1989). Multipurpose tree species for small-farm use in Nepal. *Journal of Tropical Forest Science*, 1(3), 300-301.
- Nicodemo, M. L. F., Castiglioni, P. P., Pezzopane, J. R. M., Tholon, P., & Carpanezzi, A. A. (2016). Reducing competition in agroforestry by pruning native trees. *Revista Árvore*, 40(3), 509-518.
- Nuttonson, M. Y. (1955). Wheat-climate relationships and the use of phenology in ascertaining the thermal and photo-thermal requirements of wheat. *American Institute Of Crop Ecology*.
- Ofori, F., & Stern, W. R. (1987). *Cereal-legume intercropping systems* (Vol. 41): Academic Press.
- Olive New Zealand. (2019). *The New Zealand Olive Industry*. Retrieved from <https://www.olivesnz.org.nz/wp-content/uploads/2019/05/Olives-New-Zealand-Overview-Paper-1.pdf>
- Ong, C. K., Black, C. R., Marshall, F. M., & Corlett, J. E. (1996). Principles of resource capture and utilization of light and water. Tree-crop interactions: a physiological approach. *CAB International*, 75-158.
- Patil, B. P., & Pal, M. (1988). Associative effect of intercropped legumes on pearl millet (*Pennisetum glaucum*) and their residual effect on nitrogen nutrition of succeeding bread wheat (*Triticum aestivum*). *Indian Journal of Agricultural Sciences (India)*.
- Perica, S., Goreta, S., & Selak, G. V. (2008). Growth, biomass allocation and leaf ion concentration of seven olive (*Olea europaea* L.) cultivars under increased salinity. *Scientia horticulturae*, 117(2), 123-129.
- PGG Wrightson Grain. (n.d). *Sensas*. Retrieved from <https://www.pggwrightsongrain.co.nz/Cereal-Seeds/Milling-Wheat/Sensas>
- Pons, T. L. (2000). Seed responses to light. *Seeds: the ecology of regeneration in plant communities*, 2, 237-260.
- Qiao, X., Sai, L., Chen, X., Xue, L., & Lei, J. (2019). Impact of fruit-tree shade intensity on the growth, yield, and quality of intercropped wheat. *PLoS one*, 14(4), e0203238.
- Razouk, R., Daoui, K., Ramdani, A., & Chergaoui, A. (2016). Optimal distance between olive trees and annual crops in rainfed intercropping system in northern Morocco. *J Crop Sci Res*, 1, 23-32.
- Reaumur, R. D. (1735). Observations du thermometre, faites a Paris pendant l'annee 1735, compares avec celles qui ont ete faites sous la ligne, a l'Isle de France, a Alger et en quelques-unes de nos isles de l' Amerique. *Mem. Mémoires de l'Académie des sciences*, 545-567.
- Ritchie, J. T., & Nesmith, D. S. (1991). Temperature and crop development. *Modeling plant and soil systems*, 5-29.
- Roberts, R. K., & Heady, E. O. (1982). Fertilizer demand functions for specific nutrients applied to three major US crops. *Western Journal of Agricultural Economics*, 7(1836-2016-150890), 265-278.

- Rosati, A., Caporali, S., & Paoletti, A. (2015). Fertilization with N and K increases oil and water content in olive (*Olea europaea* L.) fruit via increased proportion of pulp. *Scientia Horticulturae*, 192, 381-386.
- Roy, R. N., Finck, A., Blair, G. J., & Tandon, H. L. S. (2006). *Plant nutrition for food security. A guide for integrated nutrient management*. (Vol. 16): FAO Fertilizer and Plant Nutrition Bulletin.
- Ryan, D., Antolovich, M., Herlt, T., Prenzler, P. D., Lavee, S., & Robards, K. (2002). Identification of phenolic compounds in tissues of the novel olive cultivar hardy's mammoth. *Journal of agricultural and food chemistry*, 50(23), 6716-6724.
- Saenger, W. (1973). Structure and function of nucleosides and nucleotides. *Angewandte Chemie International Edition in English*, 12(8), 591-601.
- Saiyed, I. M., Bullock, P. R., Sapirstein, H. D., Finlay, G. J., & Jarvis, C. K. (2009). Thermal time models for estimating wheat phenological development and weather-based relationships to wheat quality. *Canadian journal of plant science*, 89(3), 429-429.
- Sale, P. J. M. (1979). Growth of potatoes (*Solanum tuberosum* L.) to the small tuber stage as related to soil temperature. *Australian Journal of Agricultural Research*, 30(4), 667-675.
- Sanchez, P. A. (1995). Science in agroforestry. *Agroforestry systems*, 30(1-2), 5-55.
- Scarpella, E., Barkoulas, M., & Tsiantis, M. (2010). Control of leaf and vein development by auxin. *Cold Spring Harbor perspectives in biology*, 2(1).
- Schmitt, J., & Wulff, R. D. (1993). Light spectral quality, phytochrome and plant competition. *Trends in Ecology & Evolution*, 8(2), 47-51.
- Schneider, E. C., & Gupta, S. C. (1985). Corn Emergence as Influenced by Soil Temperature, Matric Potential, and Aggregate Size Distribution 1. *Soil Science Society of America Journal*, 49(2), 415-422.
- Schroth, G., & Sinclair, F. L. (2002). *Trees, Crops and Soil Fertility Concepts and Research Methods*. Wallingford: CAB International.
- Sharma, N. K., Singh, R. J., & Kumar, K. (2012). Dry matter accumulation and nutrient uptake by wheat (*Triticum aestivum*, L.) under Poplar (*Populus deltoides*) Based Agroforestry System. *ISRN Agronomy*.
- Sharrow, S. H. (1999). Silvopastoralism: competition and facilitation between trees, livestock, and improved grass-clover pastures on temperate rainfed lands. In *Agroforestry in sustainable agricultural systems* (pp. 120-139): CRC Press.
- Sharrow, S. H., & Ismail, S. (2004). Carbon and nitrogen storage in agroforests, tree plantations, and pastures in western Oregon, USA. *Agroforestry Systems*, 60(2), 123-130.
- Shen, Y., McLaughlin, N., Zhang, X., Xu, M., & Liang, A. (2018). Effect of tillage and crop residue on soil temperature following planting for a Black soil in Northeast China. *Scientific reports*, 8(1), 4500.
- Singh, B., & Sharma, K. N. (2007). Tree growth and nutrient status of soil in a poplar (*Populus deltoides* Bartr.)-based agroforestry system in Punjab, India. *Agroforestry Systems*, 70(2), 125-134.
- Sirijovski, N., Olsson, U., Lundqvist, J., Al-Karadaghi, S., Willows, R. D., & Hansson, M. (2006). ATPase activity associated with the magnesium chelatase H-subunit of the chlorophyll biosynthetic pathway is an artefact. *Biochemical Journal*, 400(3), 477-484.
- Somarriba, E. (1992). Revisiting the past: an essay on agroforestry definition. *Agroforestry systems*, 19(3), 233-240.
- Somarriba, E., & Beer, J. (2011). Productivity of *Theobroma cacao* agroforestry systems with timber or legume service shade trees. *Agroforestry systems*, 81(2), 109-121.
- Sudmeyer, R. A., & Speijers, J. (2007). Influence of windbreak orientation, shade and rainfall interception on wheat and lupin growth in the absence of below-ground competition. *Agroforestry Systems*, 71(3), 201-214.

- Taiz, L., Zeiger, E., Møller, I. M., & Murphy, A. (2015). *Plant physiology and development*. Sunderland, MA: Sinauer Associates.
- Takimoto, A., Nair, P. R., & Nair, V. D. (2008). Carbon stock and sequestration potential of traditional and improved agroforestry systems in the West African Sahel. *Agriculture, Ecosystems & Environment*, 125(1-4), 159-166.
- Talhaoui, N., Taamalli, A., Gómez-Caravaca, Fernández-Gutiérrez, A., & Segura-Carretero, A. (2015). Phenolic compounds in olive leaves: Analytical determination, biotic and abiotic influence, and health benefits. *Food Research International*, 77, 92-108.
- Tejwani, K. G. (1988). Small farmers, multipurpose trees and research in India. In D. M. Withington, K. G.; Sastry (Ed.), (pp. 13-25): CB.
- Thorne, G. N. (1965). Photosynthesis of ears and flag leaves of wheat and barley. *Annals of Botany*, 29(3), 317-329.
- Thorsted, M. D., Olesen, J. E., & Weiner, J. (2006). Width of clover strips and wheat rows influence grain yield in winter wheat/white clover intercropping. *Field Crops Research*, 95(2-3), 280-290.
- Topark-Ngarm, A., & Gutteridge, R. C. (1986). Forages in Thailand. *Forages in Southeast Asian and Pacific Agriculture. ACIAR Proceedings*(12), 96-103.
- Triboi, E., & Triboi-Blondel, A. M. (2002). Productivity and grain or seed composition: a new approach to an old problem. *European journal of Agronomy*, 16(3), 163-186.
- Turnbull, J. W. (1986). *Multipurpose Australian trees and shrubs: lesser-known species for fuelwood and agroforestry*. Canberra (Australia).
- Udawatta, R. P., Kremer, R. J., Adamson, B. W., & Anderson, S. H. (2008). Variations in soil aggregate stability and enzyme activities in a temperate agroforestry practice. *Applied Soil Ecology*, 39(2), 153-160.
- USDA National Agroforestry Center. (2012). *What is agroforestry?* Retrieved from https://csfs.colostate.edu/media/sites/22/2016/01/USDA_what-is-agroforestry.pdf
- Van Asten, P. J. A., Wairegi, L. W. I., Mukasa, D., & Uringi, N. O. (2011). Agronomic and economic benefits of coffee–banana intercropping in Uganda’s smallholder farming systems. *Agricultural systems*, 104(4), 326-334.
- Van Wijk, W. R., Larson, W. E., & Burrows, W. C. (1959). Soil Temperature and the Early Growth of Corn from Mulched and Unmulched Soil 1. *Soil Science Society of America Journal*, 23(6), 428-434.
- Von Kiparski, G. R., Lee, L. S., & Gillespie, A. R. (2007). Occurrence and fate of the phytotoxin juglone in alley soils under black walnut trees. *Journal of environmental quality*, 36(3), 709-717.
- Wahua, T. A. T., & Miller, D. A. (1978). Effects of Intercropping on Soybean N₂-Fixation and Plant Composition on Associated Sorghum and Soybeans 1. *Agronomy Journal*, 70(2), 292-295.
- Waimea Nurseries. (2014). Retrieved from <https://commercial.waimeanurseries.co.nz/assets/Uploads/Comm-Olives/Olive-Brochure-2014.pdf>
- Wang, J., Zhang, Y., Liu, C., Tan, Y., Zhang, Y., Chen, L., & Chen, Y. (2015). Wheat grain filling characteristics and quality traits in wheat-apricot intercropping field in Southern Xinjiang. *Acta agriculturae Boreali-occidentalis sinica (Chinese with English abstract)*, 24(7), 44-50.
- Wang, Q., & Shogren, J. F. (1992). Characteristics of the crop-Paulownia system in China. *Agriculture, ecosystems & environment*, 39(3-4), 145-152.
- Watt, M., & Evans, J. R. (1999). Linking development and determinacy with organic acid efflux from proteoid roots of white lupin grown with low phosphorus and ambient or elevated atmospheric CO₂ concentration. *Plant physiology*, 120(3), 705-716.
- Weir, A. H., Bragg, P. L., Porter, J. R., & Rayner, J. H. (1984). A winter wheat crop simulation model without water or nutrient limitations. *The Journal of Agricultural Science*, 102(2), 371-382.

- Wibisono, M. G., Veneklaas, E., Mendham, D. S., & Hardiyanto, E. B. (2015). Nitrogen fixation of *Acacia mangium* Willd. from two seed sources grown at different levels of phosphorus in an Ultisol, South Sumatra, Indonesia. *Southern Forests: a Journal of Forest Science*, 77(1), 59-64.
- Willey, R. W., Natarajan, M., Reddy, M. S., Rao, M. R., Nambiar, P. T. C., Kannaiyan, J., & Bhatnagar, V. S. (1983). *Intercropping studies with annual crops*. London: Pitman.
- Wintrode, P. L., & Arnold, F. H. (2001). Temperature adaptation of enzymes: lessons from laboratory evolution. *Advances in protein chemistry*, 55, 161-225.
- Xiao, D., Qi, Y., Li, Z., Wang, R., Moiwo, J. P., & Liu, F. (2017). Impact of thermal time shift on wheat phenology and yield under warming climate in the Huang-Huai-Hai Plain, China. *Frontiers of Earth Science*, 11(1), 148-155.
- Xie, P. J., Huang, L. X., Zhang, C. H., You, F., & Zhang, Y. L. (2013). Reduced pressure extraction of oleuropein from olive leaves (*Olea europaea* L.) with ultrasound assistance. *Food and Bioproducts processing*, 93, 29-38.
- Yang, T., Duan, Z. P., Zhu, Y., Gan, Y. W., Wang, B. J., Hao, X. D., . . . Li, L. H. (2019). Effects of distance from a tree line on photosynthetic characteristics and yield of wheat in a jujube tree/wheat agroforestry system. *Agroforestry Systems*, 93(4), 1545-1555.
- Yin, R. a. H., Q. (1997). The spatial and temporal effects of Paulownia intercropping: the case of northern China. *Agrofor Syst*, 37, 91-109.
- Yun, L., Bi, H., Gao, L., Zhu, Q., Ma, W., Cui, Z., & Wilcox, B. P. (2012). Soil moisture and soil nutrient content in walnut-crop intercropping systems in the Loess Plateau of China. *Arid Land Research and Management*, 26, 285-296.
- Zadoks, J. C., Chang, T. T., & Konzak, C. F. (1974). A decimal code for the growth stages of cereals. *Weed research*, 14(6), 415-421.
- Zake, J., Pietsch, S. A., Friedel, J. K., & Zechmeister - Boltenstern, S. (2015). Can agroforestry improve soil fertility and carbon storage in smallholder banana farming systems? *Journal of Plant Nutrition and Soil Science*, 178(2), 237-249.
- Zamora, D. S., Jose, S., Nair, P. K. R., Jones, J. W., Brecke, B. J., & Ramsey, C. L. (2008). *Interspecific competition in a pecan-cotton alley-cropping system in the southern United States: Is light the limiting factor?* Dordrecht: Springer.
- Zhang, D. S., Zhang, L. Z., Liu, J. G., Han, S., Wang, Q., Evers, J., . . . Li, L. (2014). Plant density affects light interception and yield in cotton grown as companion crop in young jujube plantations. *Field Crops Res* 169, 132-139.
- Zhang, L. W., Zhong, W. J., Jiang, Y. W., Zhao, T. T., Song, Z., Qian, Y. D., & Jiang, C. C. (2018). Effects of nitrogen-water coupling on rice yield and quality during tillering stage. *Jiangsu Agricultural Sciences*, 46(7), 55-58.
- Zhang, Q., L., M., L., & Ping, S., Z. (2008). Biological nitrogen fixation and its application in sustainable agriculture. *Biotechnology Bulletin*, 2.
- Zhao, X. (2014). Effect of diurnal temperature variation on dry matter production and yield of tomato in greenhouse. *Nanjing University of Information Science and Technology*.
- Zheng, Y. F., Xu, J. X., Wu, R. J., Zheng, Y. F., Xu, J. X., & Wu, R. J. (2013). Effects of shading on dry matter accumulation and distribution of winter wheat. *Chinese Agricultural Meteorology*, 34(1), 64-73.
- Zhou, J., M. (Ed.) (2013). *Dictionary of Soil Science*. Science Press.
- Zilio, D. M., Bartocci, S., Di Giovanni, S., Servili, M., Chiariotti, A., & Terramoccia, S. (2015). Evaluation of dried stoned olive pomace as supplementation for lactating Holstein cattle: effect on milk production and quality. *Animal production science*, 55(2), 185-188.

Appendices

Appendix 1 ANOVA results for each soil moisture measurements from each plots from 5/10/2018 to 19/06/2019.

| Treatment | 5/10/2018 | 9/10/2018 | 16/10/2018 | 26/10/2018 | 31/10/2018 | 13/11/2018 | 22/11/2018 | 30/11/2018 | 7/12/2018 | 13/12/2018 | 27/12/2018 | 16/01/2019 | 24/01/2019 |
|-----------|-----------|-----------|------------|------------|------------|------------|------------|------------|-----------|------------|------------|------------|------------|
| Fallow | 31.47 | 30.7 | 32.3 | 30.33 | 33.57 | 31.63 | 36.93 | 35.1 | 34.27 | 31.98 | 31.78 | 26.2 | 18.33 |
| W | 30.83 | 28 | 33.47 | 32.37 | 34.33 | 30.53 | 36.17 | 34.7 | 32.78 | 29.92 | 31.73 | 25.8 | 18.33 |
| W/C | 31.1 | 30.3 | 33.17 | 31.8 | 34.83 | 31.17 | 36.53 | 35.3 | 32.32 | 30.25 | 31.87 | 24.4 | 17.33 |
| Mean | 31.13 | 29.7 | 32.98 | 31.5 | 34.24 | 31.11 | 36.54 | 35 | 33.12 | 30.72 | 31.79 | 25.5 | 17.99 |
| P-Value | 0.893 | 0.604 | 0.807 | 0.248 | 0.628 | 0.571 | 0.891 | 0.975 | 0.483 | 0.615 | 0.994 | 0.767 | 0.845 |
| LSD | 3.66 | 7.43 | 5.007 | 2.9 | 3.46 | 2.696 | 4.367 | 7.34 | 4.27 | 5.872 | 3.493 | 6.97 | 1.022 |

| 8/02/2019 | 26/02/2019 | 14/03/2019 | 8/04/2019 | 9/04/2019 | 17/04/2019 | 30/04/2019 | 8/05/2019 | 29/05/2019 | 7/06/2019 | 19/06/2019 |
|-----------|------------|------------|-----------|-----------|------------|------------|-----------|------------|-----------|------------|
| 25.2 | 15.05 | 17.4 | 25.2 | 27.93 | 25.53 | 29.67 | 24.05 | 21.97 | 33.28 | 31.73 |
| 29.52 | 17.73 | 17.35 | 29.47 | 27.45 | 27.47 | 30.48 | 25.97 | 25.13 | 32.97 | 32.25 |
| 29.27 | 15.43 | 17.63 | 29.27 | 28 | 26.82 | 29.75 | 24.83 | 23.17 | 33.02 | 31.92 |
| 27.99 | 16.07 | 17.46 | 27.98 | 27.79 | 26.61 | 29.97 | 24.95 | 23.42 | 33.09 | 31.97 |
| 0.066 | 0.482 | 0.794 | 0.066 | 0.913 | 0.644 | 0.932 | 0.609 | 0.254 | 0.89 | 0.96 |
| 3.948 | 6.068 | 1.066 | 3.925 | 3.852 | 5.501 | 6.569 | 5.043 | 4.476 | 1.931 | 5.044 |

Appendix 2 ANOVA results for stomatal conductance of olive tree leaves across treatments from 8/12/2018 to 19/06/2019.

| Cultivar | Treatment | 8/12/2018 | 15/12/2018 | 12/12/2018 | 1/01/2019 | 11/01/2019 | 21/01/2019 | 30/01/2019 | 12/02/2019 |
|----------------------------|-----------|------------|------------|------------|-----------|------------|------------|------------|------------|
| Barnea | Fallow | 264.7 | 271.9 | 202 | 267 | 301 | 284 | 208 | 269 |
| Barnea | W | 303.5 | 276 | 215.8 | 311 | 337 | 294.1 | 298 | 171 |
| Barnea | W+C | 334.4 | 265 | 290.9 | 419 | 414 | 404.8 | 403 | 243 |
| Mean | | 300.9 | 271 | 236.3 | 332 | 351 | 327.6 | 303 | 228 |
| Frantoio | Fallow | 281.7 | 239.1 | 171.9 | 373 | 362 | 288.1 | 284 | 226 |
| Frantoio | W | 307.8 | 274.4 | 234.7 | 430 | 382 | 340.4 | 314 | 321 |
| Frantoio | W+C | 303.5 | 263.6 | 212.4 | 449 | 376 | 341.3 | 392 | 287 |
| Mean | | 297.6 | 259 | 206.3 | 417 | 373 | 323.2 | 330 | 278 |
| Leccino | Fallow | 251.2 | 220.7 | 222.7 | 335 | 298 | 301.6 | 258 | 191 |
| Leccino | W | 238.2 | 211.5 | 214.2 | 346 | 286 | 287.2 | 237 | 180 |
| Leccino | W+C | 234 | 226.9 | 149.4 | 273 | 300 | 251.5 | 265 | 225 |
| Mean | | 241.1 | 219.7 | 195.4 | 318 | 373 | 280.1 | 253 | 198 |
| P-value treatment | | 0.554 | 0.792 | 0.632 | 0.434 | 0.288 | 0.198 | 0.006 | 0.172 |
| P-value Cultivar | | 0.011 | <.001 | 0.226 | 0.06 | 0.035 | 0.116 | 0.035 | 0.003 |
| P-value Cultivar*Treatment | | 0.44 | 0.297 | 0.073 | 0.289 | 0.477 | 0.062 | 0.13 | 0.114 |
| LSD | | 39.78 | 19.52 | 85.91 | 146.5 | 59 | 79.6 | 42.5 | 56.7 |
| 20/02/2019 | 5/03/2019 | 19/03/2019 | 28/03/2019 | 9/04/2018 | 1/05/2019 | 10/05/2019 | 23/05/2019 | 3/06/2019 | 19/06/2019 |
| 255.8 | 224.4 | 271.6 | 275.8 | 304.3 | 270.3 | 264.8 | 196.1 | 189 | 165.8 |
| 195.3 | 179.4 | 241.3 | 253.7 | 285.6 | 278.9 | 229.9 | 165.7 | 172.1 | 163.5 |
| 235.6 | 215.6 | 363.5 | 317.6 | 289.6 | 341.2 | 348.7 | 200.8 | 243.9 | 207.4 |
| 228.9 | 206.5 | 292.1 | 282.4 | 293.2 | 296.8 | 281.1 | 187.5 | 201.7 | 178.9 |
| 194.6 | 180.6 | 281.9 | 233.6 | 224.6 | 221 | 185.4 | 163.2 | 170.9 | 141.3 |
| 279.7 | 255.4 | 313.1 | 293.9 | 263.4 | 199.8 | 177.5 | 142.6 | 176.6 | 135 |
| 252.9 | 263.4 | 331.9 | 303.9 | 307.3 | 309.8 | 275.1 | 182.2 | 209.9 | 202 |
| 242.4 | 233.1 | 309 | 277.1 | 265.1 | 243.5 | 212.7 | 162.7 | 185.8 | 159.4 |
| 172.7 | 162.7 | 255.8 | 217 | 212 | 252.8 | 230.6 | 160.7 | 188.1 | 172.4 |
| 197.3 | 162.5 | 253.8 | 243.1 | 234 | 213.3 | 204.1 | 159.9 | 195.1 | 165.6 |
| 216.3 | 193.9 | 244.1 | 247 | 243.9 | 216.4 | 193.6 | 162 | 173.7 | 167.2 |
| 195.5 | 173 | 251.3 | 235.7 | 230 | 227.5 | 209.5 | 160.9 | 185.6 | 168.4 |
| 0.193 | 0.264 | 0.228 | 0.104 | 0.316 | 0.079 | 0.013 | 0.381 | 0.044 | 0.008 |
| 0.153 | 0.081 | 0.032 | 0.002 | 0.002 | 0.018 | 0.007 | 0.057 | 0.622 | 0.733 |
| 0.207 | 0.382 | 0.1 | 0.069 | 0.137 | 0.165 | 0.082 | 0.62 | 0.364 | 0.792 |
| 74.17 | 82.33 | 42.5 | 24.29 | 30.17 | 46.53 | 44.5 | 49.99 | 22.41 | 17.87 |

Appendix 3 Fitted lines for leaves SPAD reading and chlorophyll concentration of three olive tree cultivars.

